The Science and Engineering of an Operational Tsunami Forecasting System – One Component of a Comprehensive Program to Reduce the Impact of Another Indian Ocean Mega-disaster

Frank González

Leader, Tsunami Research Program

National Oceanic and Atmospheric Administration
Pacific Marine Environmental Laboratory
Seattle, WA

Argonne National Laboratory Seminar
6 April 2005
Argonne, Illinois

Fatalities

Center of Excellence in Disaster Management and Humanitarian Assistance

Emergency Report : January 8, 2005

Damage Estimated to be $13.6B

26 Dec 2004 Sumatra Mega-disaster *(Titov MOST Model)*

QuickTime™ and a
Sorenson Video 3 decompressor
are needed to see this picture.

Impacts

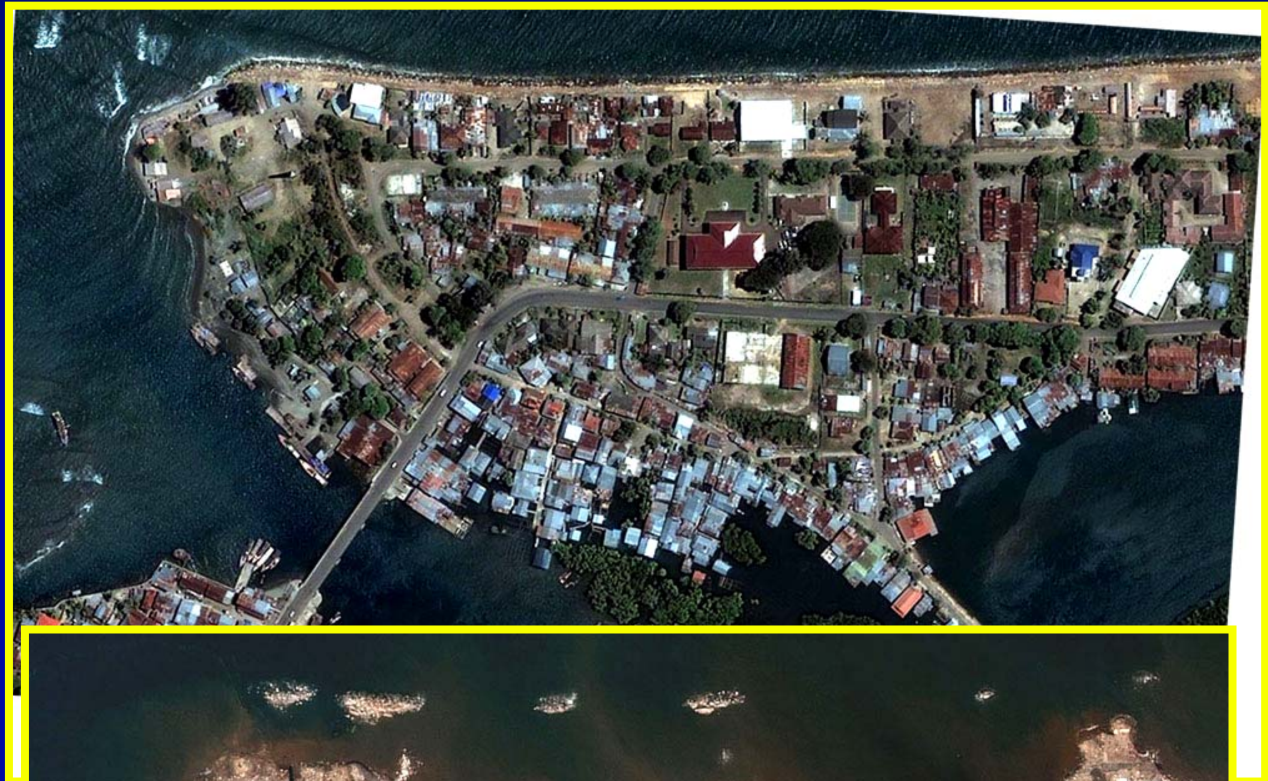
Sri Lanka
& Phuket, Thailand

Kho Kah,
Thailand

Banda Aceh, Sumatra

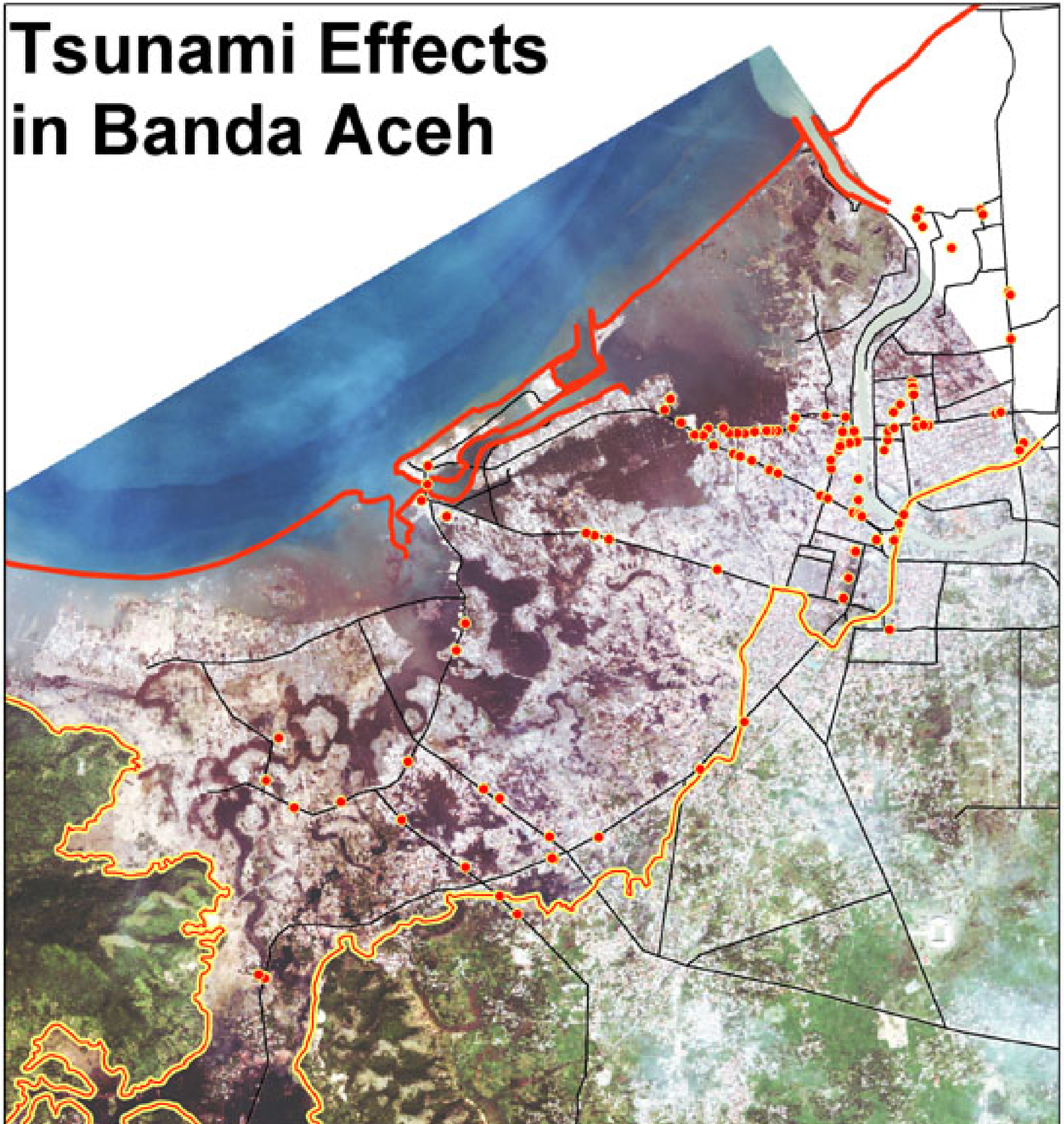
QuickTime™ and a
Video decompressor
are needed to see this picture.

Worst tsunami destruction was not videotaped.



Digital Globe Quickbird Satellite Photos

Tsunami Effects in Banda Aceh



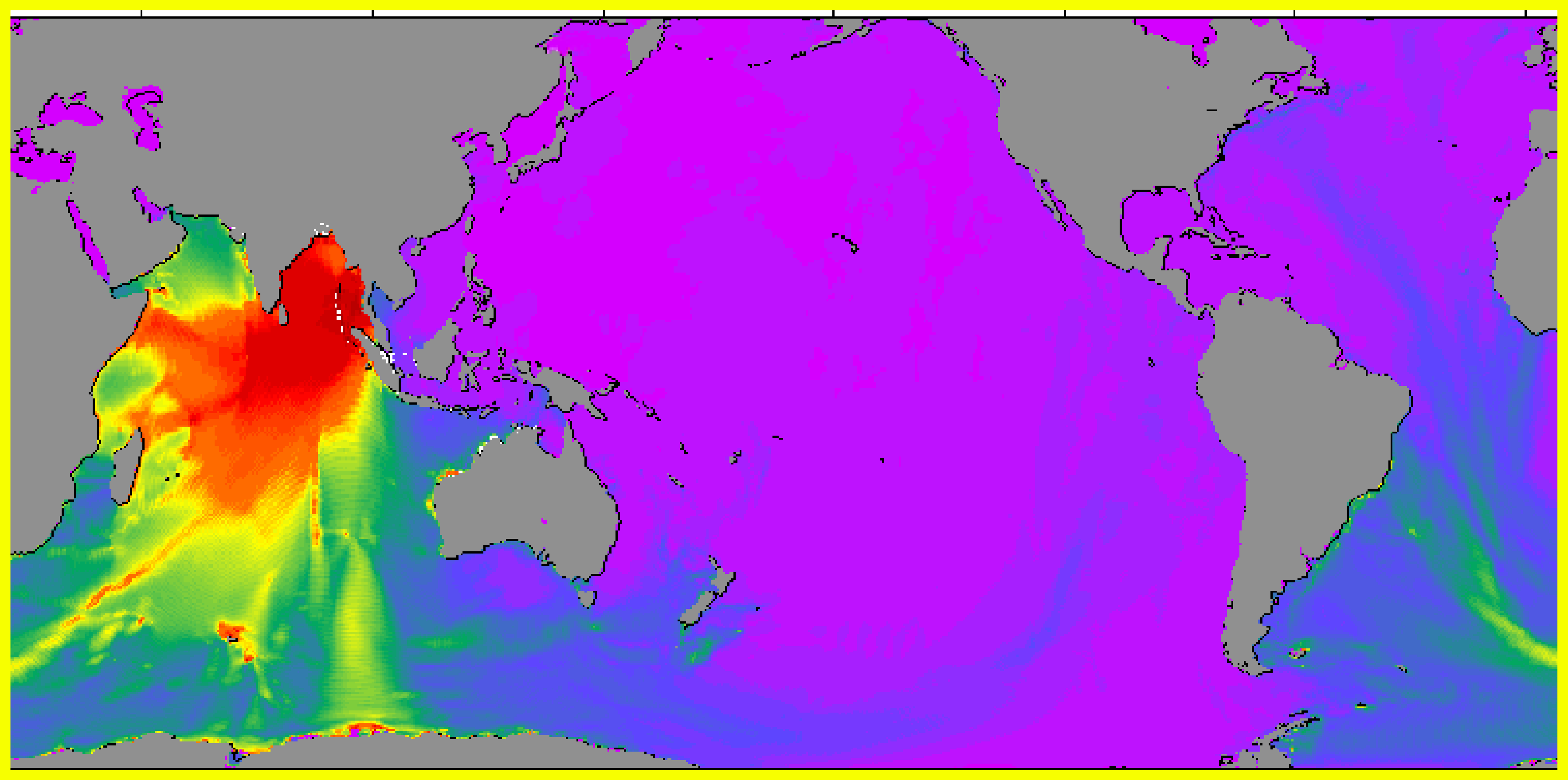
Credit:
Dr. Jose Borrero
USC,USA

Slide Not Available

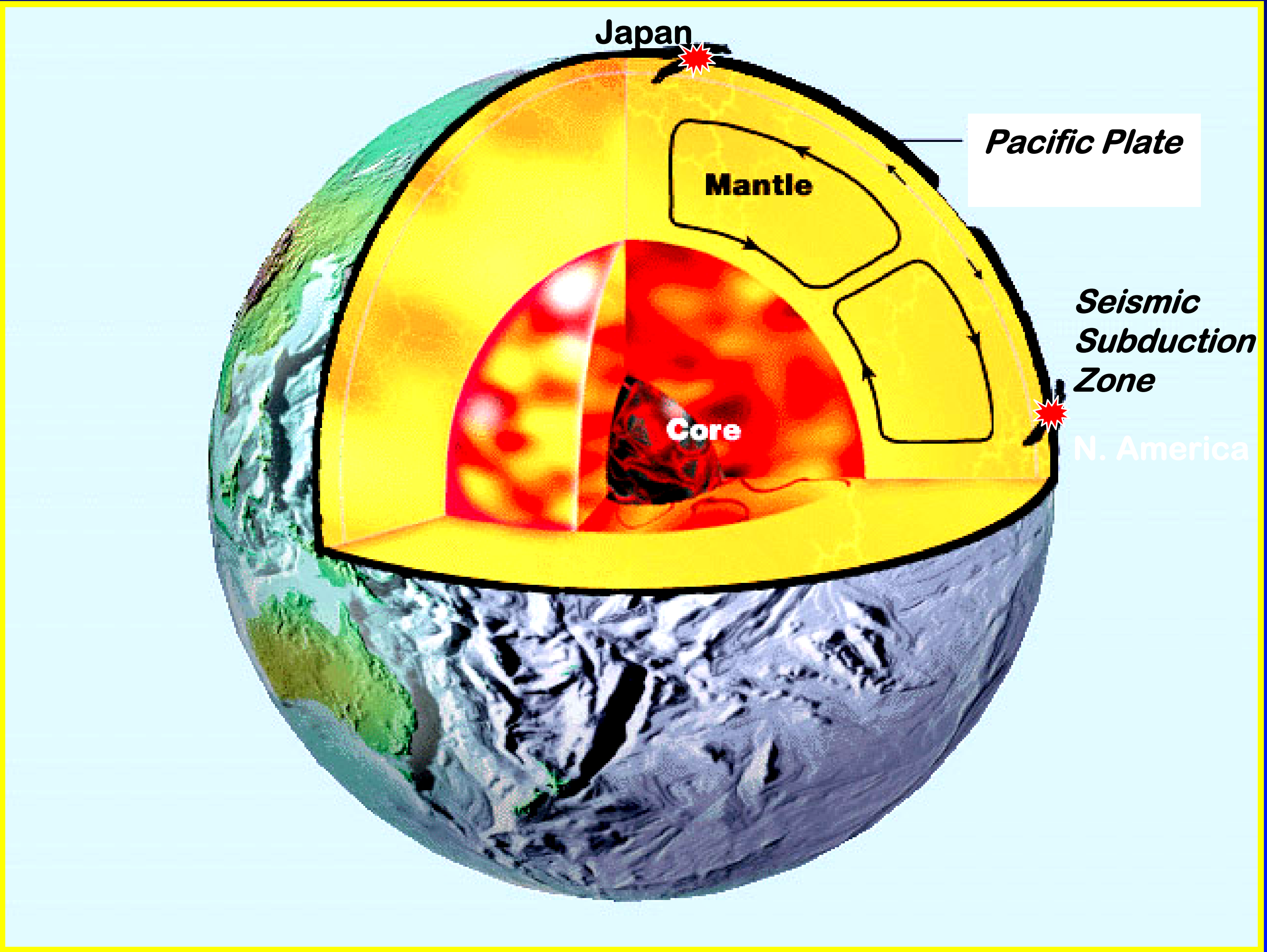
26 Dec 04 Tsunami Simulation *(V. Titov, D. Arcas)*

QuickTime™ and a
Photo decompressor
are needed to see this picture.

Max Tsunami Height



TSUNAMIS … Inevitable, and “*Born of Fire*”

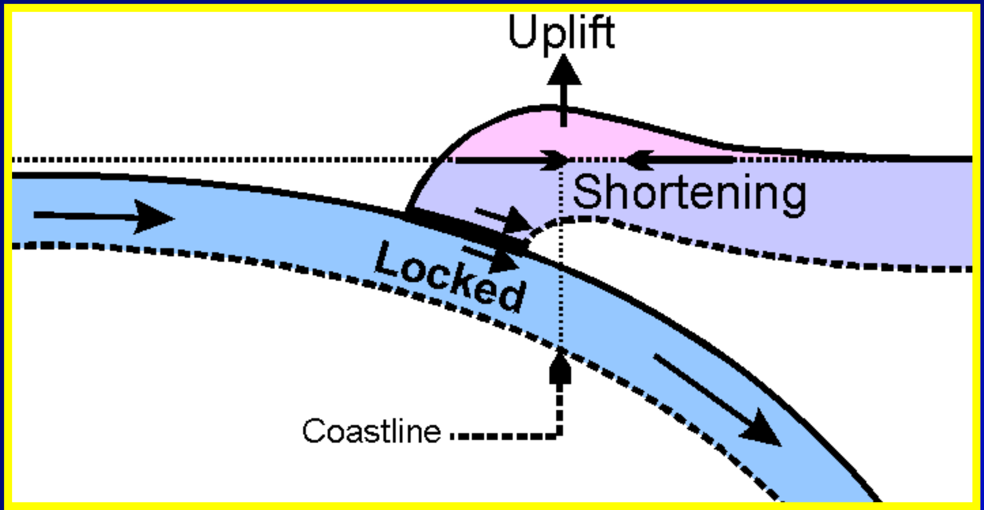


Definition

A tsunami is a series of long water waves generated when water is displaced by an impulsive geophysical event.

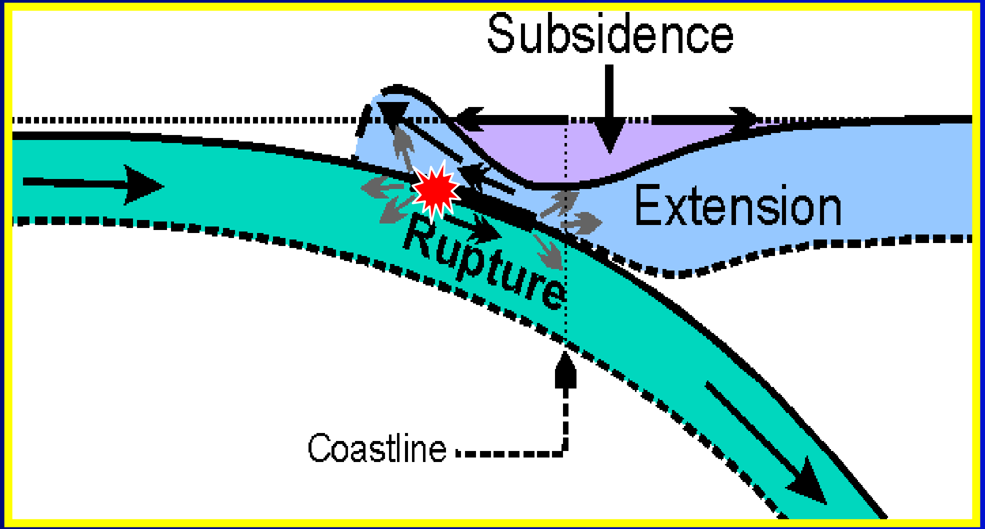
Sources: Earthquakes, Landslides, Volcanoes, Meteors, …

Subduction Zone Earthquake Cycle



1. *Interseismic* Period:

10's - 100's of years between earthquakes

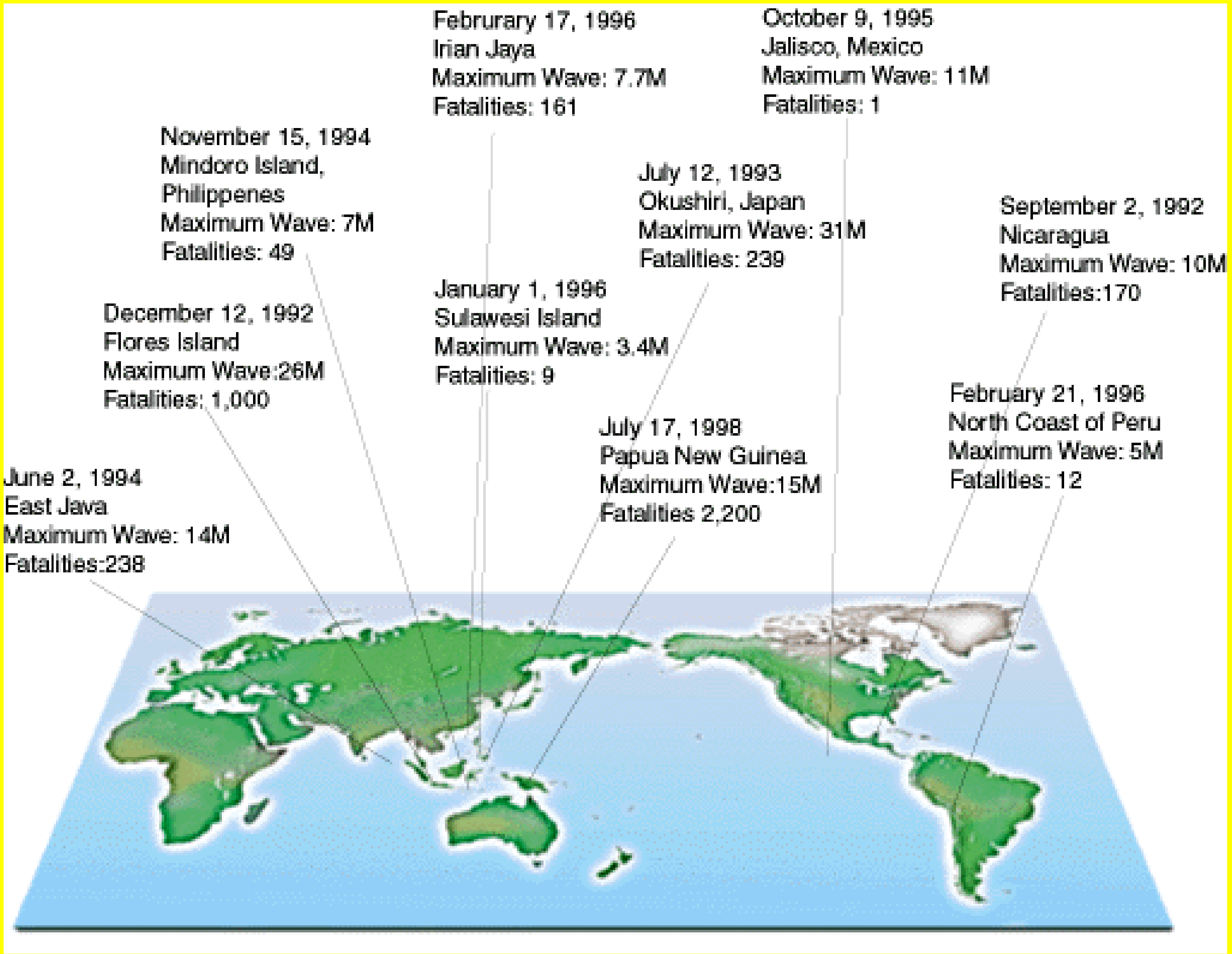


2. *Coseismic* Period:

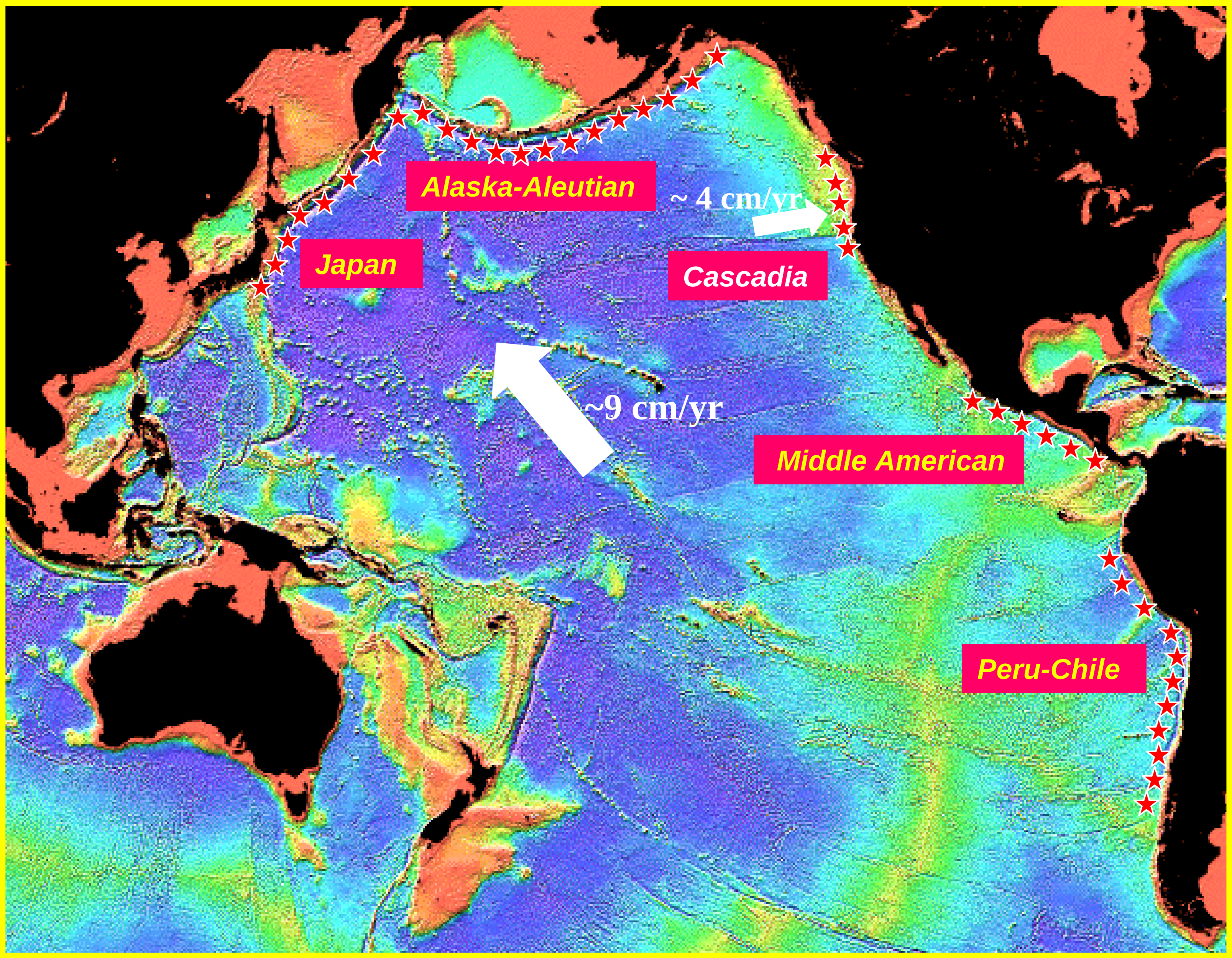
A few minutes of Earthquake Rupture

(Courtesy, Geological Survey of Canada)

Ten Destructive Tsunamis Since 1990 Killed More than 4,000



Pacific Seismic Zones



Northwest Tsunami Hazards

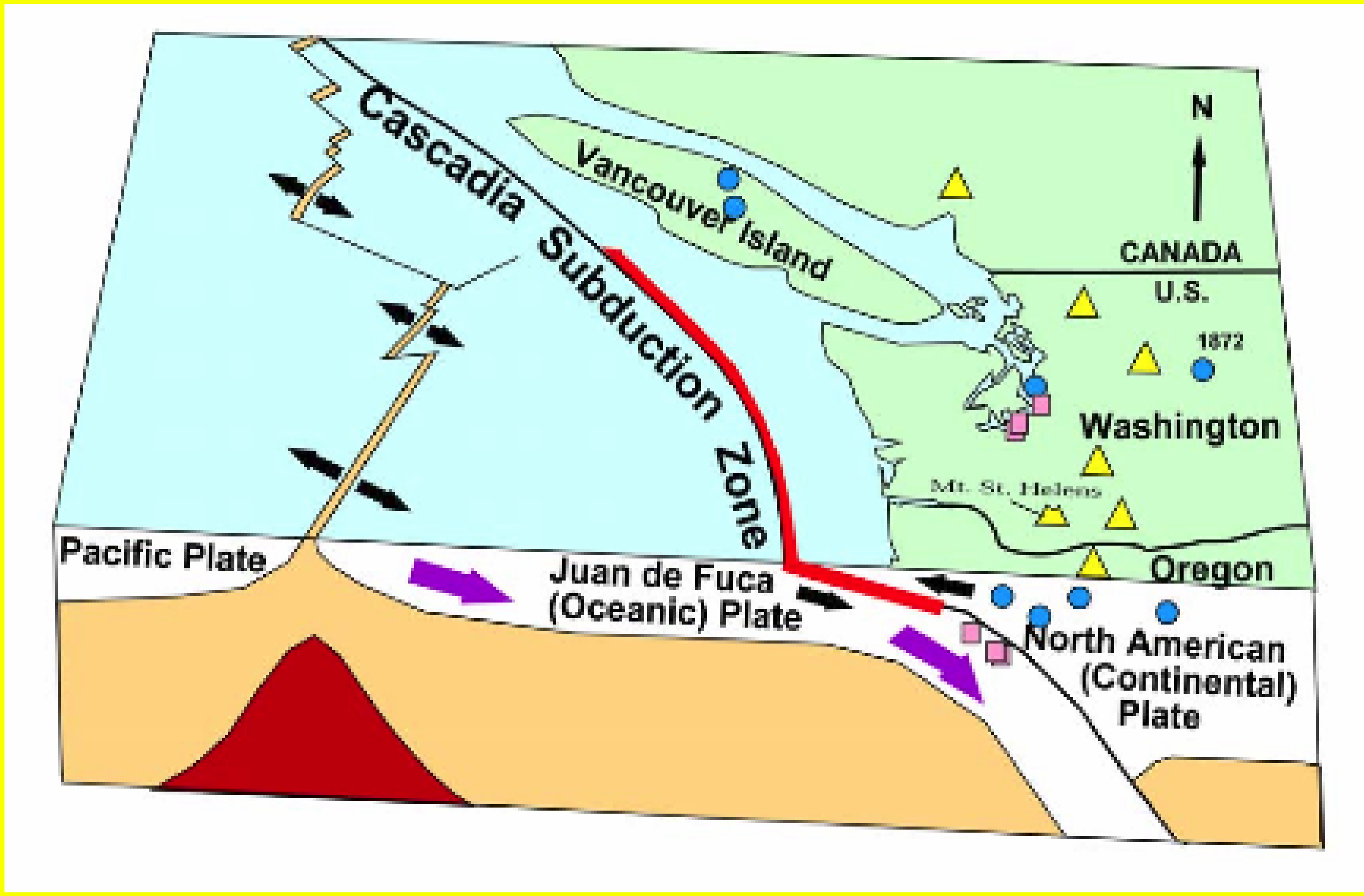
“ Local” Sources (Warning ~ 5-30 minutes)

1. Cascadia Subduction Zone
   - M ~ 9
   - Centuries recurrence times
2. Puget Sound Faults
   - M ~ 7.6
   - Millenia recurrence times ?

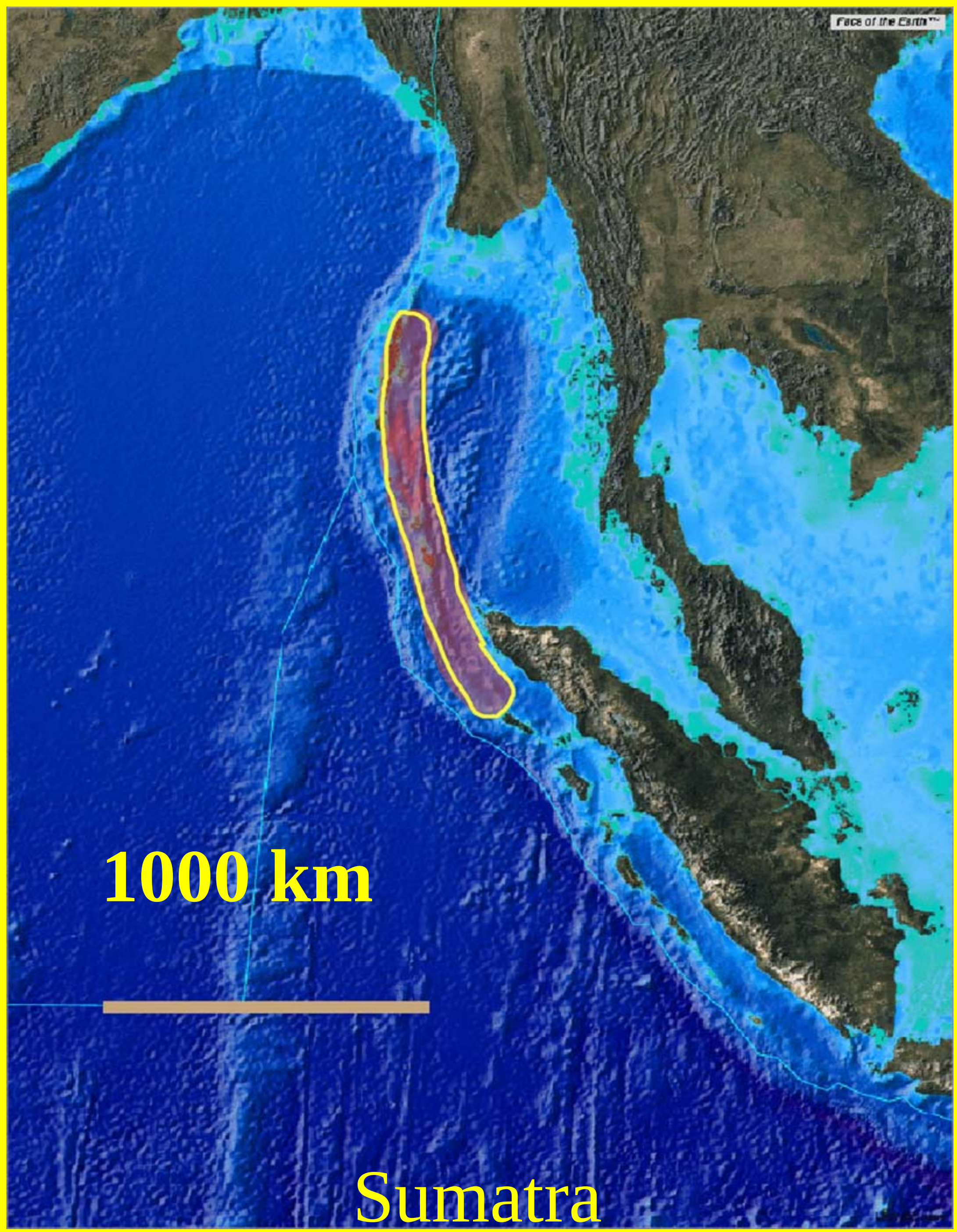
“Distant” Sources (Warning ~ 1-4 hours)

3. Alaska-Aleutian Subduction Zone
   - M ~ 8 +
   - Decades recurrence times

Cascadia Subduction Zone



Sumatra/Cascadia



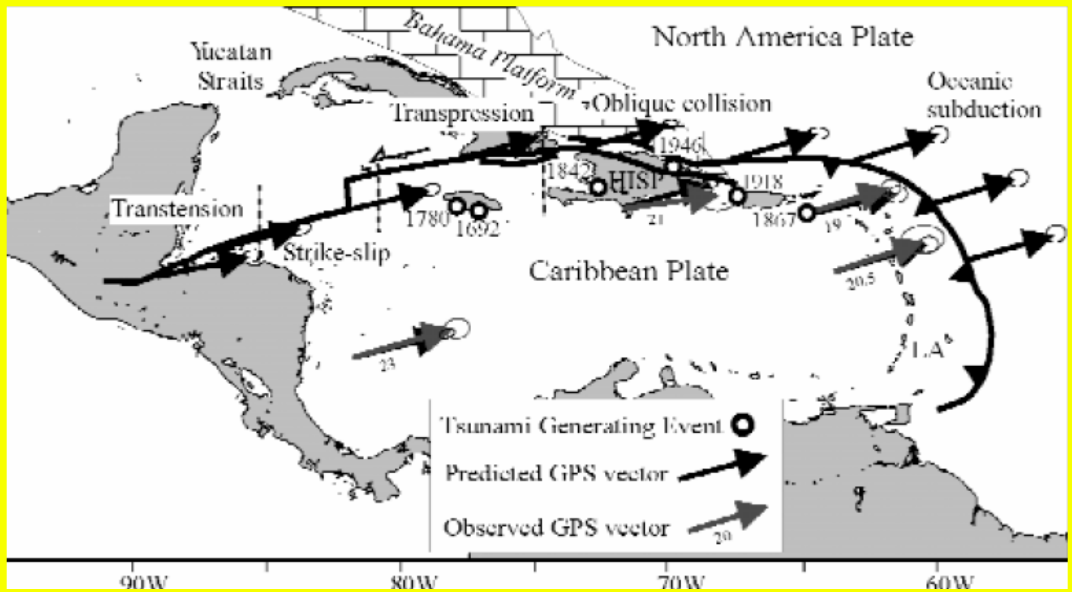
Credit: Lori Dengler

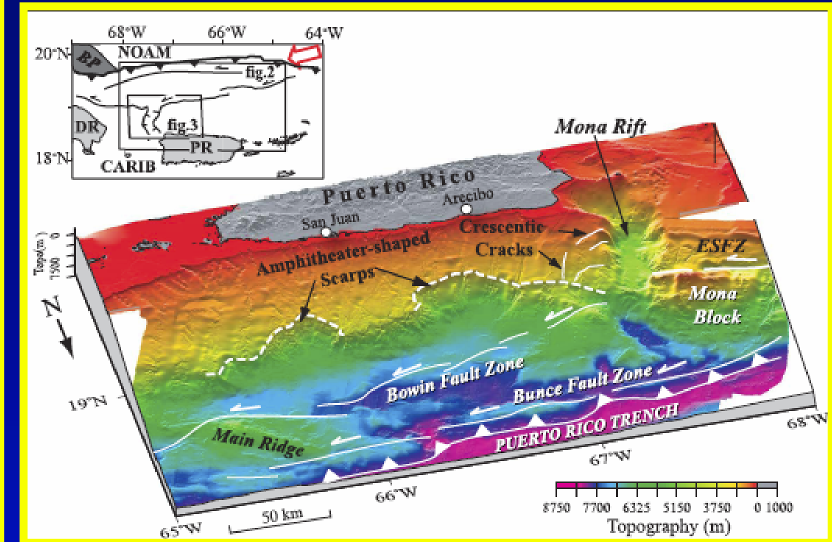
Tsunami Statistics by Ocean

- 1900 - Present
- Significant tsunamis defined as
  - High Validity Index
  - > 1 m height

Ocean	Significant Tsunamis	All Tsunamis
Pacific	210 (88%)	604 (88%)
Indian	8 (3%)	32 (5%)
Atlantic	21 (9%)	51 (7%)
Total	239 (100%)	687 (100%)

Analysis by Paul Whitmore, West Coast and Alaska Tsunami Warning Center
Data from NOAA/National Geophysical Data Center Historical Tsunami Database



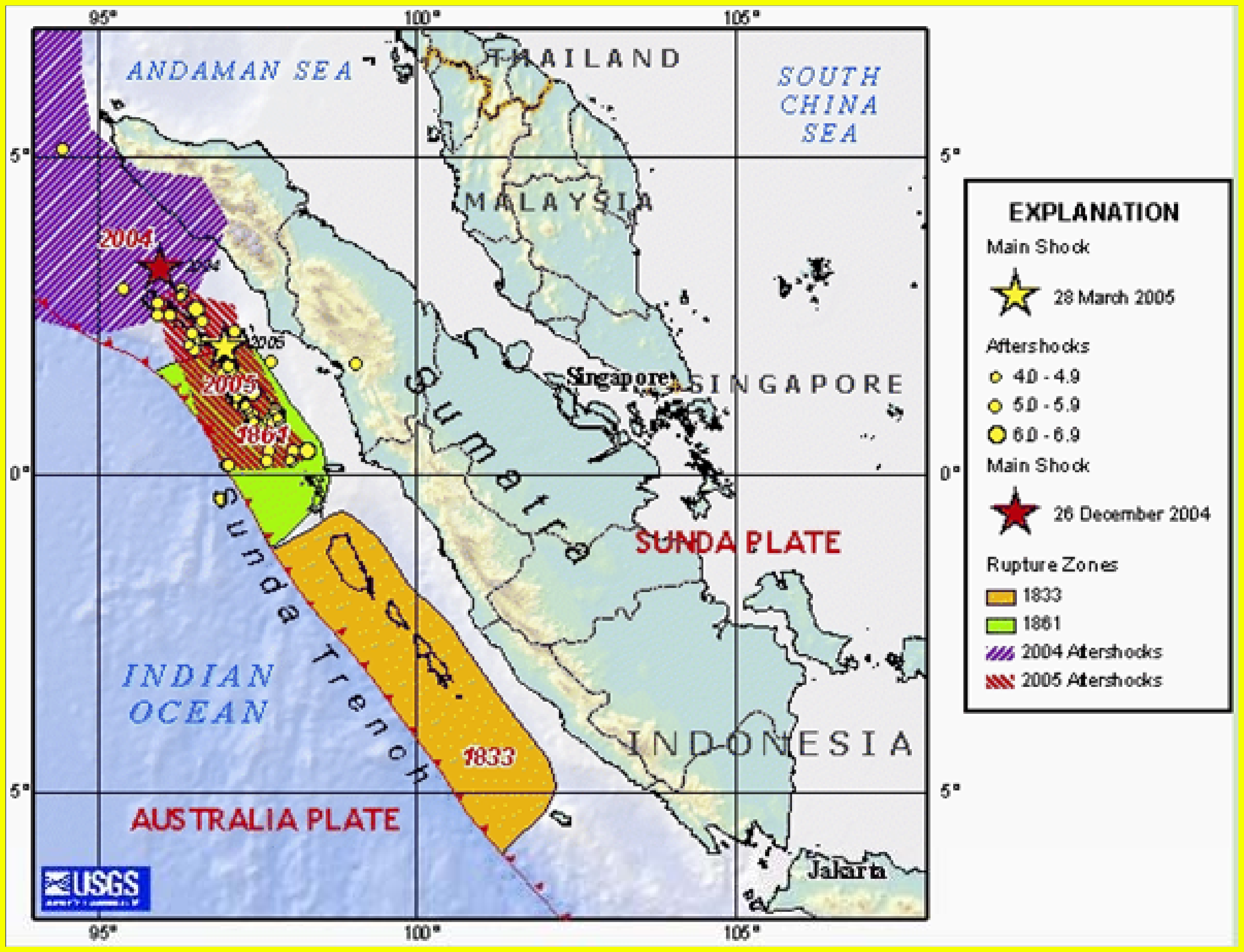


Year	Location	M	Tsu Ht (m)	Deaths: Eq + Tsu (?)	Deaths: Eq	Deaths: Tsu
1692	Port Royal, Jamaica			2000		
1780	S. Coast Jamaica		3			10 ? (Hurr.)
1842	Hispaniola		3.1 - 5	100's		
1867	Puerto Rico	7.5	2.4 - 12.1			17
1918	Hispaniola-Puerto Rico	7.3	6	156	116	40
1946	N.E. Coast, Dom. Rep.	8.1		1800		

N. Caribbean Eq/Tsu Events

Grindley, et al., EOS, 3/22/05.

28 March 2005 Sumatra 8.7



McCloskey, et al., NATURE, 17 March 2005

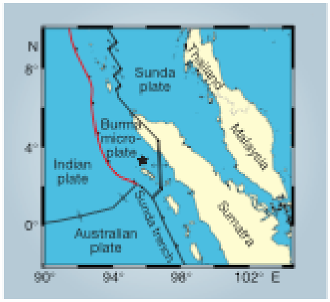
Earthquake risk from co-seismic stress

Last year's Indonesian earthquake has increased seismic hazard in the region.

Following the massive loss of life caused by the Sumatra–Andaman earthquake in Indonesia and its tsunami, the possibility of a triggered earthquake on the contiguous Sunda trench subduction zone is a real concern. We have calculated the distributions of co-seismic stress on this zone, as well as on the neighbouring, vertical strike–slip Sumatra fault, and find an increase in stress on both structures that significantly boosts the already considerable earthquake hazard posed by them. In particular, the increased potential for a large subduction-zone event in this region, with the concomitant risk of another tsunami, makes the need for a tsunami warning system in the Indian Ocean all the more urgent.

Inspection of the aftershock distribution and evidence from recent inversions reveal that the Sumatra–Andaman earthquake of 26 December 2004 ruptured almost 0.25 million square kilometres of the Indian plate/Burma microplate subduction zone (Fig. 1), generating a tsunami. The current death toll is in the region of 300,000.

Subduction-zone earthquakes are often coupled: in the Nankai trough subduction zone to the southeast of Japan, for example, five of the seven large earthquakes on the Nankaido segment in the past 1,500 or so years were accompanied by similar events on the contiguous Tonankai/Tokai segment within five years, and three of those occurred in the same year[1]. This observation is entirely consistent with stress interaction, which has been shown to explain the space–time juxtaposition of large earthquakes[2]. The destructive Izmit earthquake (magnitude 7.4) southeast of Istanbul, for example, was triggered by stress increases of less than 2 bars that were due to earlier local events[3]; in turn, this triggered the Düzce earthquake (magnitude 7.1), which occurred three months later[4].



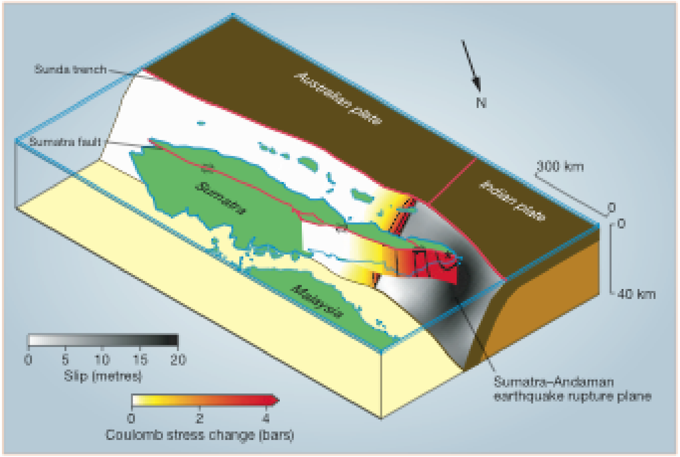


Figure 2 The Sumatran subduction zones with the overlying plates removed. Calculated three-dimensional stresses have been projected on to a diagram of the three-dimensional structural geometry and geography of the region. Grey-scale values on the rupture plane represent the amount of slip in metres experienced on the southernmost 450 km of the Sumatra–Andaman earthquake. Colour-scale values represent the co-seismic stress changes on the Sunda-trench subduction zone and the Sumatra fault. Stress contours (in black) show 2-bar intervals, starting from a maximum of 8 bars on both faults. Essential features of the calculated stresses are robust to changes in the slip distribution in recent long-period inversions, which show continuation of slip to the north for a total rupture length of about 1,200 km (ref. 10). Black asterisk indicates location of the devastated Indonesian city of Banda Aceh.

Previous work on the palaeoseismology of the Sunda trench has indicated that this area may already be advanced in the seismic cycle[5]. The northern section of the Sumatra fault has not experienced any large earthquakes for at least the past 100 years either.

Waveform-inversion studies reveal a strongly heterogeneous slip distribution for the Sumatra–Andaman earthquake, with maximum displacements being of the order of 20 m and the majority of the slip being concentrated on the southernmost 500 km or so of the rupture[6]. We used this slip distribution to calculate the stress perturbation tensor, which was then resolved on the structures of interest. Results show a stress increase of up to 5 bars in the 50 km of the Sunda trench next to the rupture zone, but they also show a strong positive loading of up to 9 bars for about 300 km on the Sumatra fault near the city of Banda Aceh (Fig. 2).

The results indicate that although a subduction-zone event in the Sunda trench has been made more likely by the Sumatra–Andaman earthquake, at present the increase in stress is localized on the north of this segment. The effect might be expected to spread further south in the months ahead … 1833 and 1861 are known to have produced fatal tsunamis[8].

The co-seismic stress perturbation on the Sumatra fault described here is significantly larger and of a greater spatial extent than the stresses that are believed to have triggered large, strike–slip earthquakes in the North Anatolian Fault Zone[2]. Considering past activity and the observed structural complexity on the northern Sumatra fault[9], an earthquake of magnitude 7–7.5 on this structure would seem to represent the greatest immediate threat.

John McCloskey, Suleyman S. Nalbant, Sandy Steacy

School of Environmental Sciences, University of Ulster, Coleraine, County Derry BT52 1SA, UK

e-mail: j.mccloskey@ulster.ac.uk

1. Rydelek, P. A. & Sacks, I. S. *Earth Planet. Sci. Lett.* **206**, 289–296 (2003).
2. Stein, R. S., Barka, A. A. & Dieterich, J. H. *Geophys. J. Int.* **128**, 594–604 (1997).
3. Nalbant, S. S., Hubert, A. & King, G. C. P. *J. Geophys. Res.* **103**, 24469–24486 (1998).
4. Hubert-Ferrari, A. et al. *Nature* **404**, 269–272 (2000).
5. Zachariasen, J., Sieh, K., Taylor, F. W., Edwards, R. L. & Hantoro, W. S. *J. Geophys. Res.* **104**, 895–919 (1999).
6. Ji, C. http://neic.usgs.gov/neis/bulletin/neic_slav_ff.html (2005).
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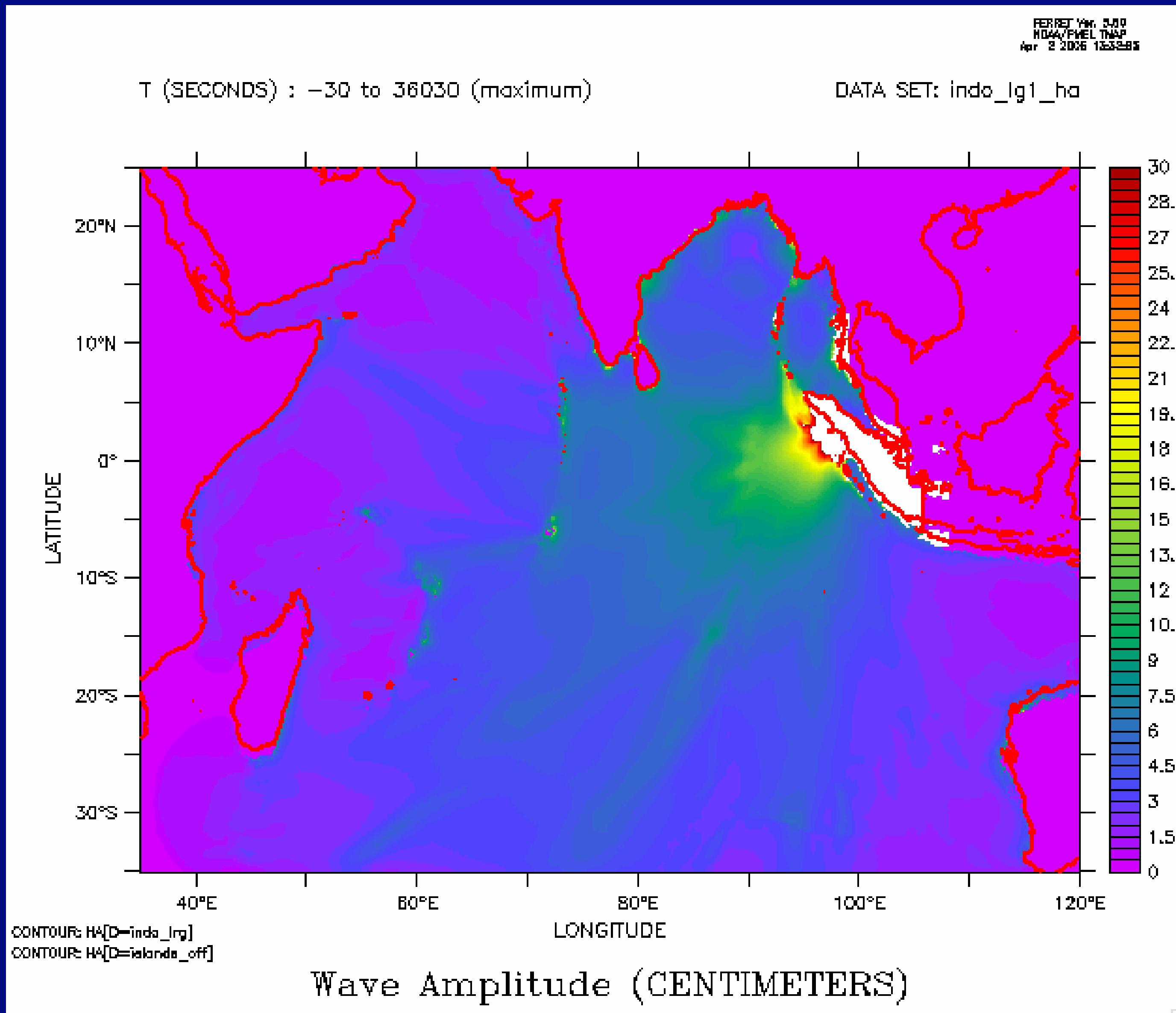
8. Newcomb, K. R. & McCann, W. R. *J. Geophys. Res.* **92**, 421–439

28 March 2005



USGS "Felt Reports"

At least 1000 people killed, 300 injured and 300 buildings destroyed on Nias; 100 people killed, many injured and several buildings damaged on Simeulue; 200 people killed in Kepulauan Banyak; 3 people killed, 40 injured and some damage in the Meulaboh area, Sumatra. A 3-meter tsunami damaged the port and airport on Simeulue. Tsunami runup heights as high as 2 meters were observed on the west coast of Nias and 1 meter at Singkil and Meulaboh, Sumatra. Felt (VI) at Banda Aceh and (V) at Medan. At least 10 people were killed during evacuation of the coast of Sri Lanka. Felt (IV) along the west coast of Malaysia; (IV) at Bangkok and (III) at Phuket, Thailand; (III) at Singapore; (III) at Male, Maldives. The quake was also felt in the Andaman and Nicobar Islands, India and in Sri Lanka. Tsunami wave heights (peak to trough) recorded from selected tide stations: about 40 cm on Panjang, Indonesia; about 25 cm at Colombo, Sri Lanka; 40 cm on Hanimadu, 18 cm at Male and 10 cm at Gan, Maldives. Initial observations indicate about 1 meter of subsidence on the coast of Kepulauan Banyak as well as 1 meter of uplift on the coast of Simeulue. Seiches were observed on ponds in West Bengal, India.

20050328 Sumatra Summary Maps

3 tsunami waves reported at Gusong Bay, Simeulue Island

12 foot tsunami wave reported at Gusong Bay, Simeulue Island by Brian Willy (resident)

Gusong Bay, Simeulue Island

West Sumatra International Tsunami Survey Team will arrive at Nias at approximately 2300 31 March UTC

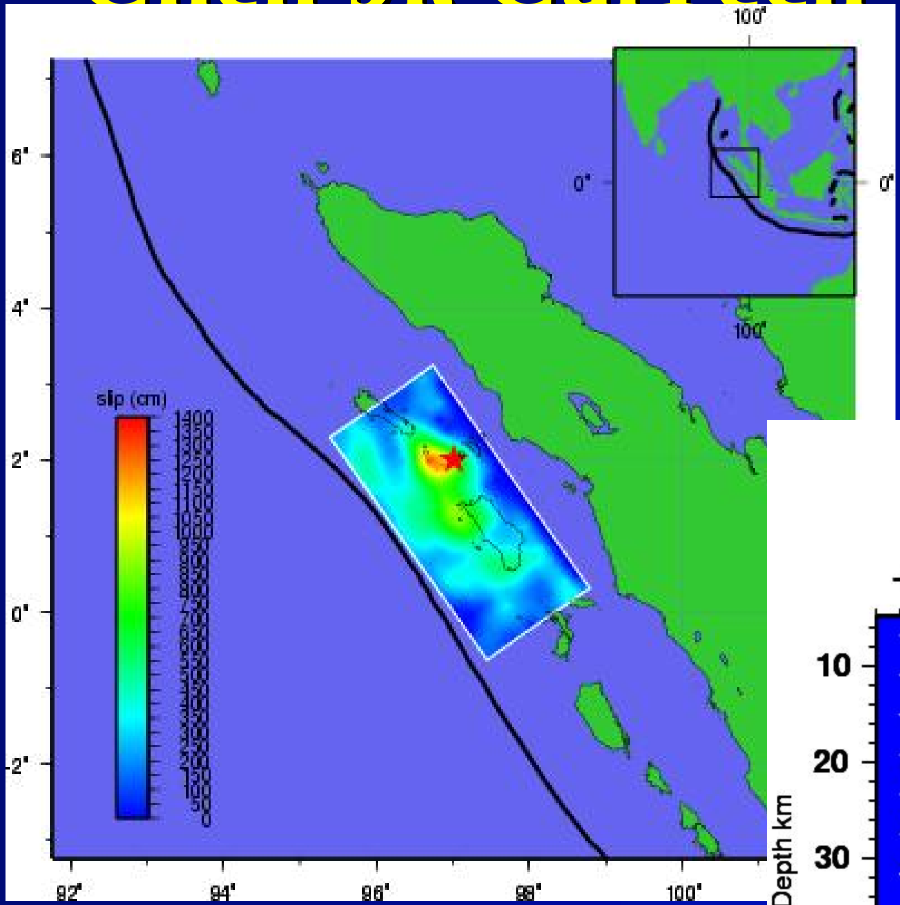
USGS

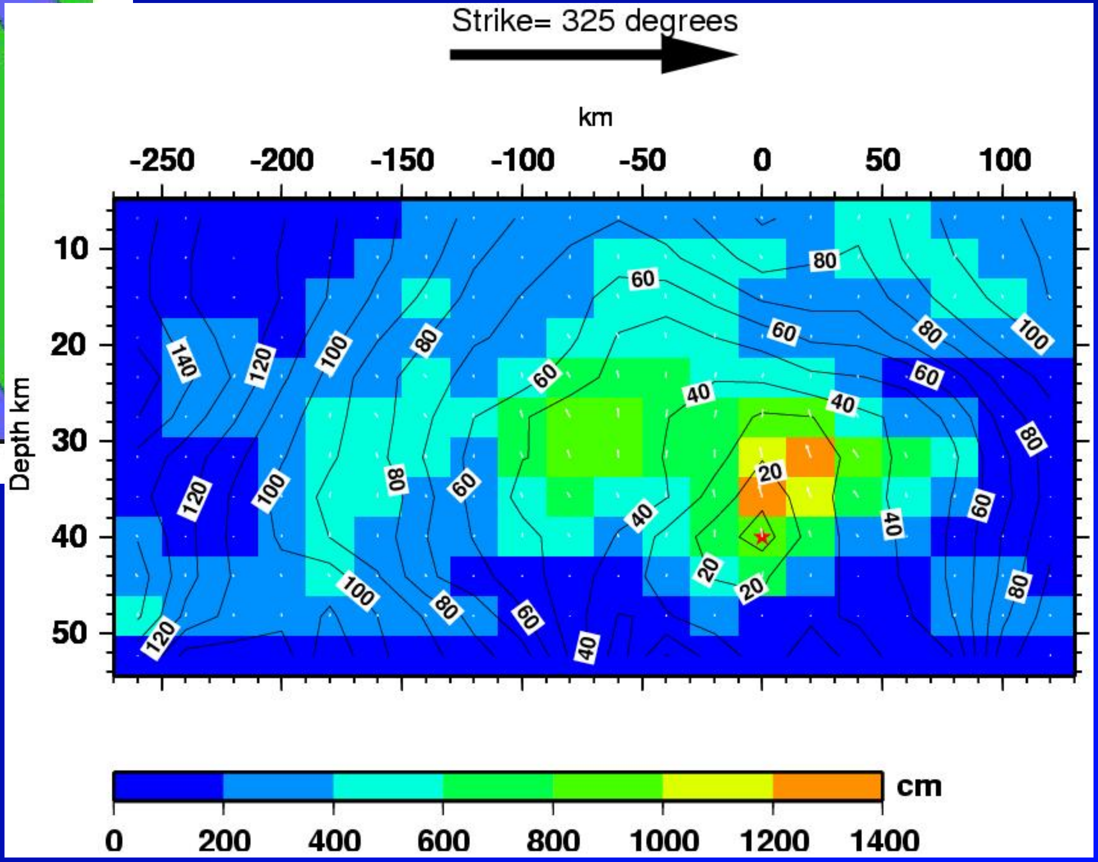
Gusong Bay, Simeule - Uplift. New Beach

Subsidence of Sarangbaung, Indonesia

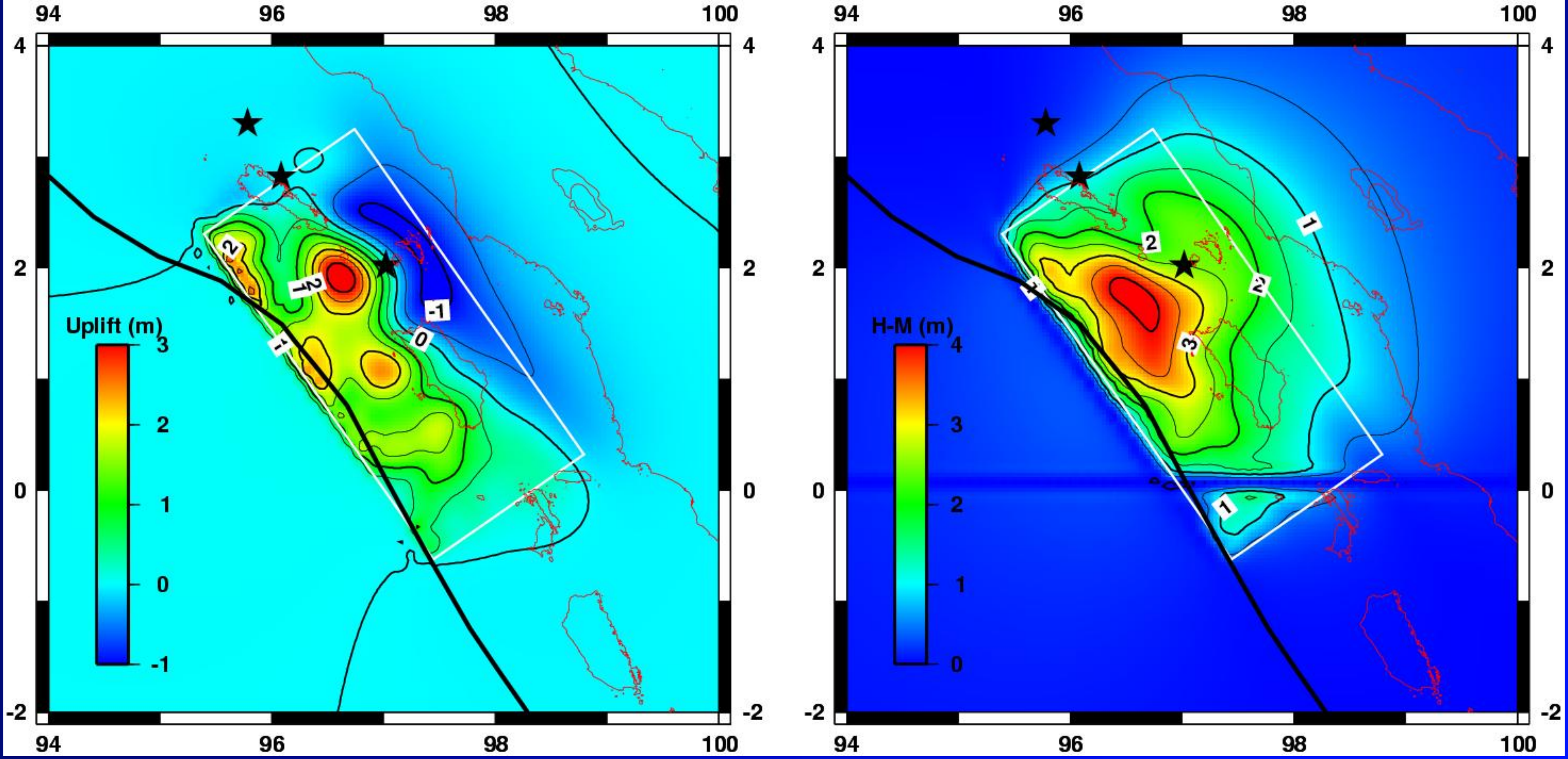
Sarangbaung subsided 1.65 meters during the 28 March 2005 earthquake. Etienne Kingsley (USGS contractor) and Gegar Prasetya (Tsunami Research Center/Coastal Dynamic Research Center - BPPT) are standing at the high tide line prior to the 28 March earthauake. Subsidence is fairly consistent around the island. The 28 March earthquake produced a 1 meter tsunami that inundated ~200 m inland.

Chen Ji, CalTech & USGS Slip Model





Displacemen



U.S. National Tsunami Hazard Mitigation Program

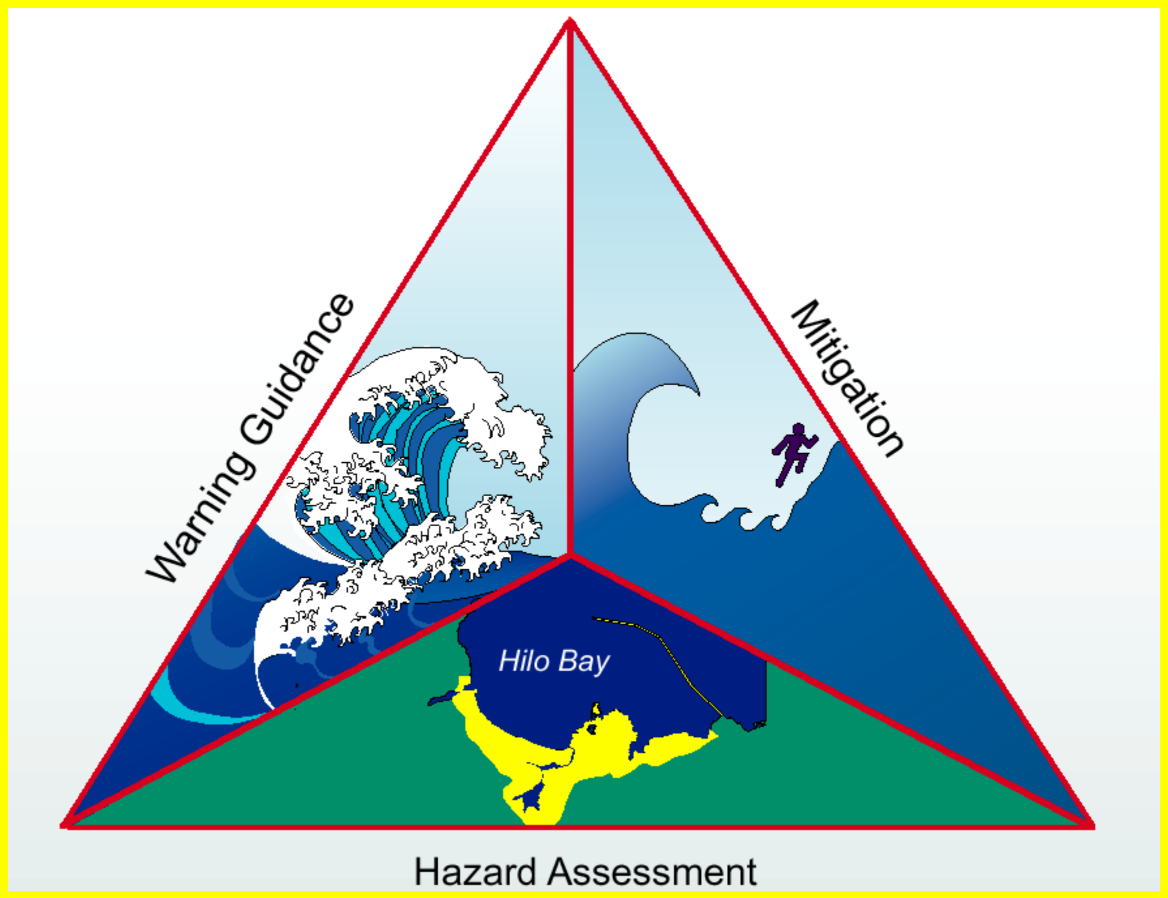
Reduce the Impact of Tsunamis on U.S. Coastal Communities

State Agencies

Alaska California Hawaii Oregon Washington

Federal Agencies

- *National Oceanic and Atmospheric Admin.*
- *U.S. Geological Survey*
- *Federal Emergency Management Agency*



Frank González, NOAA TIME Center, PMEL, Seattle, WA

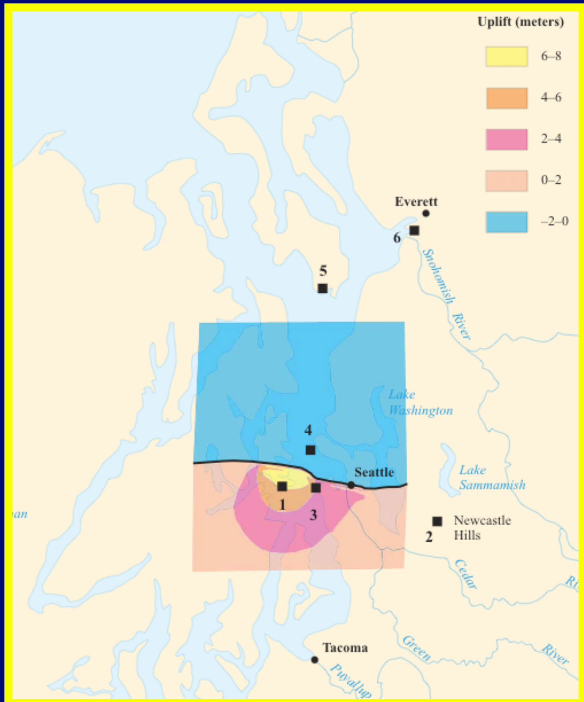
Goal

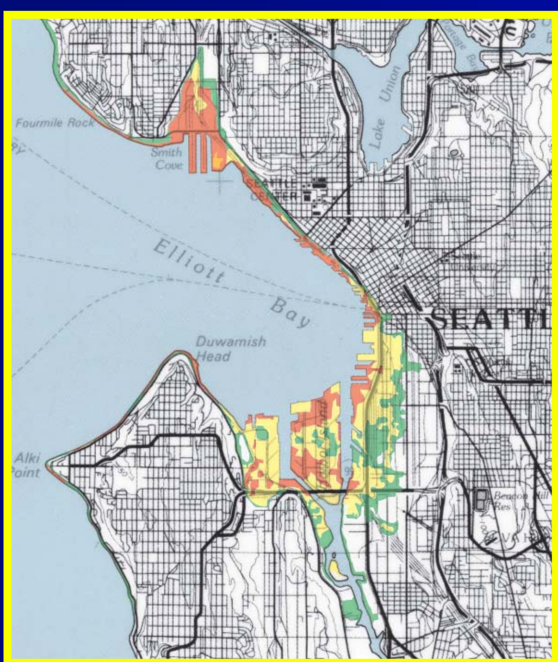
Reduce Fatalities through:

- **Hazard Assessment**
  - **- Historical and pre-historic studies**
  - **- "What if" modeling studies**
- **Education, Training, Mitigation**
  - **- Brochures, signs, etc.**
  - **- Community workshops, meetings**
- **Tsunami Warning System**
  - **- Tsunami Forecasting System**
    - ***Real-time Measurements***
    - ***Forecast Modeling***

• Hazard Assessment

Seattle Fault Tsunami, ~ 900 A.D.





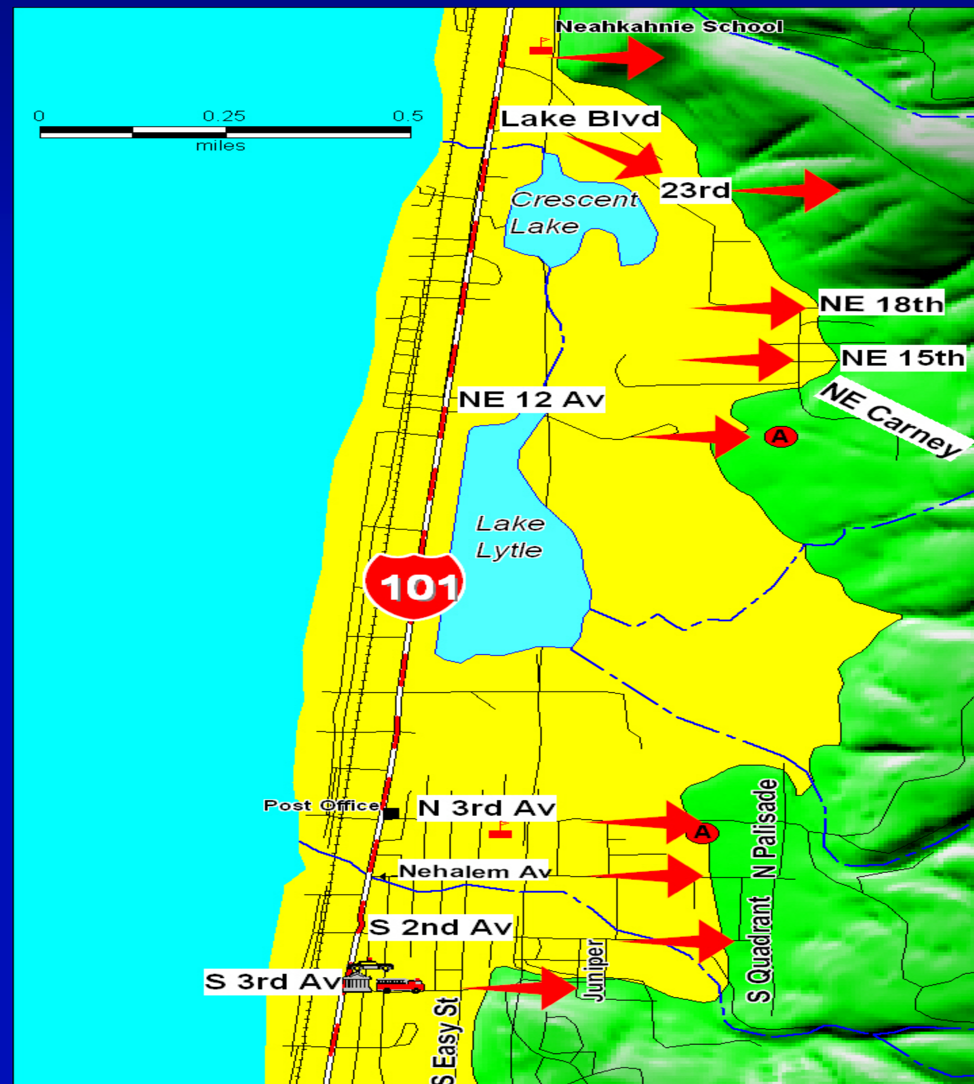
QuickTime™ and a
Sorenson Video 3 decompressor
are needed to see this picture.

- **Education, Training, Mitigation**

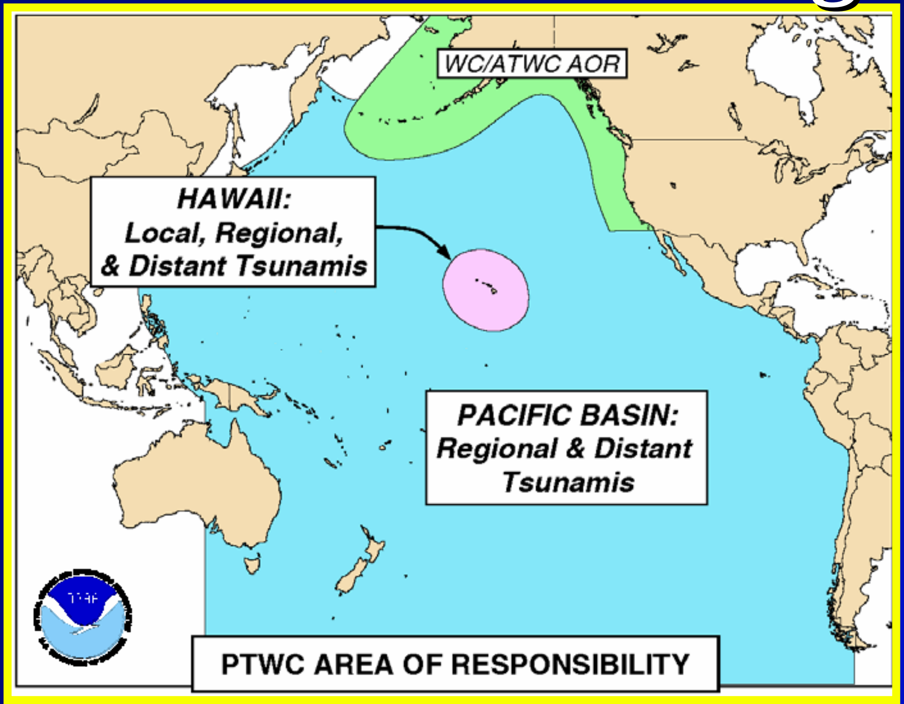
Rockaway Beach Evacuation Map

LEGEND

- Evacuation Zone
- Evacuation Route
- School
- Fire Station
- Police Station
- City Hall
- Assembly Area



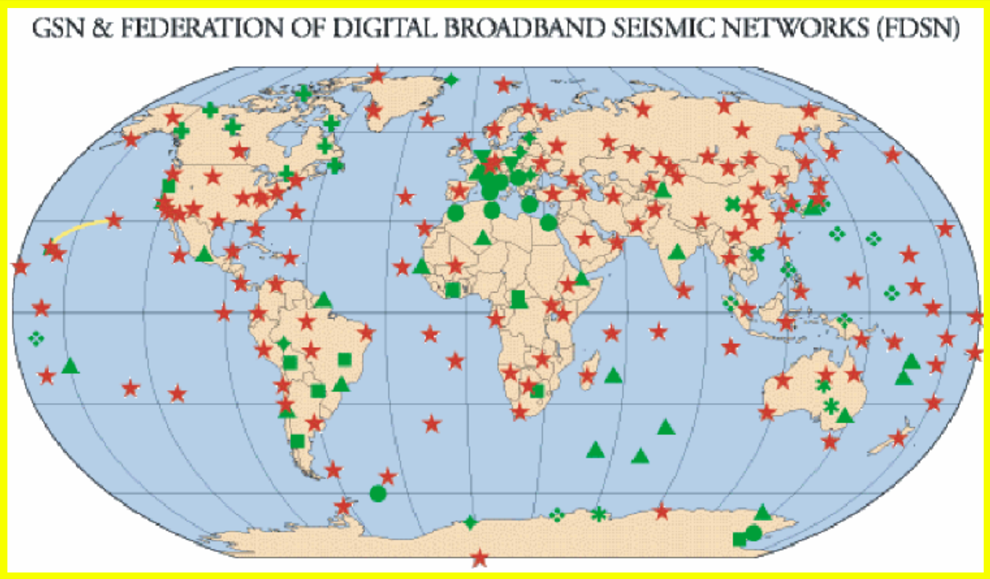
• Tsunami Warning System

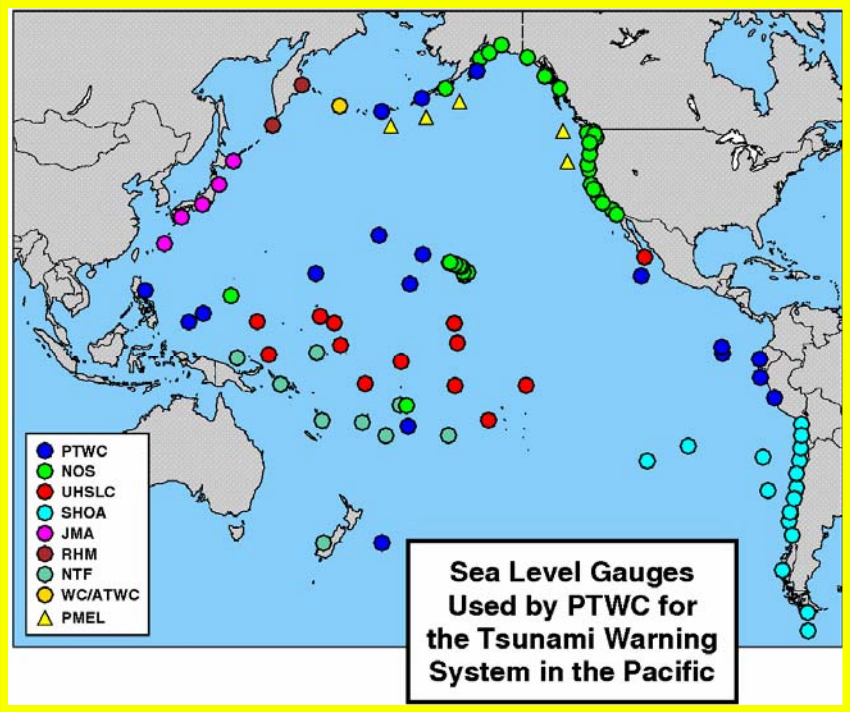


TWS = Seismic + Tide Gage Nets

Problems:

- Seismometers do not measure tsunamis
- Tide Gages IN community, NOT BETWEEN source and community

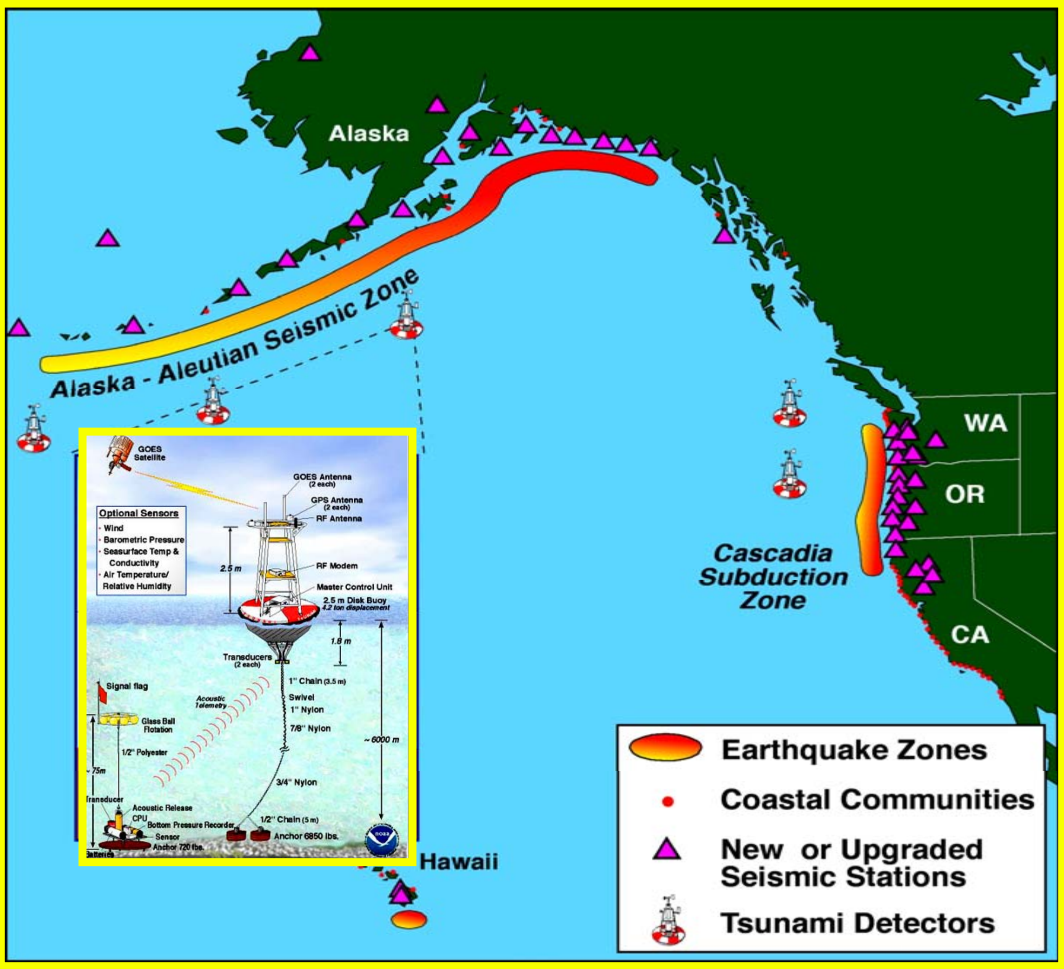


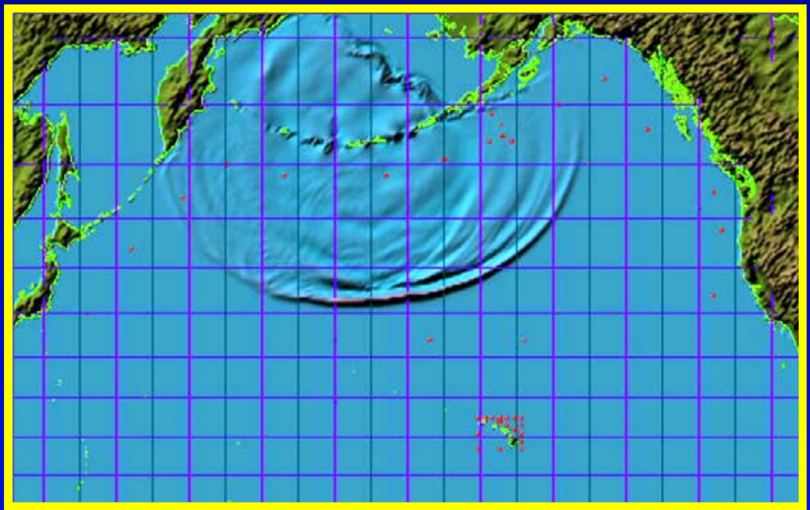


Short-term **I**nundation **F**orecasting for **T**sunamis

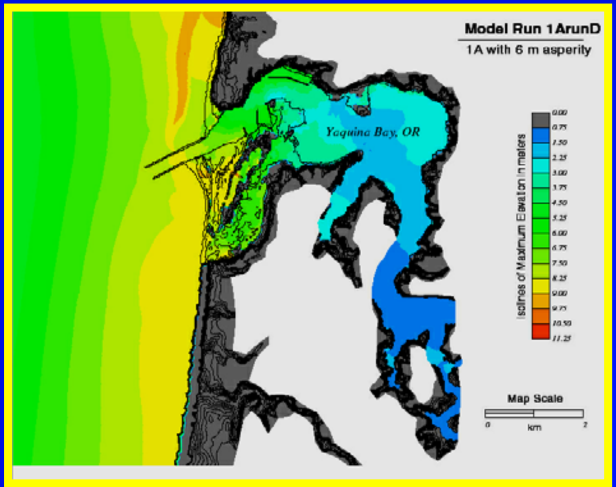
By Combining

Real-time Tsunami & Seismic Data **+** ***Model Simulations Database***





For Site-specific Forecasts



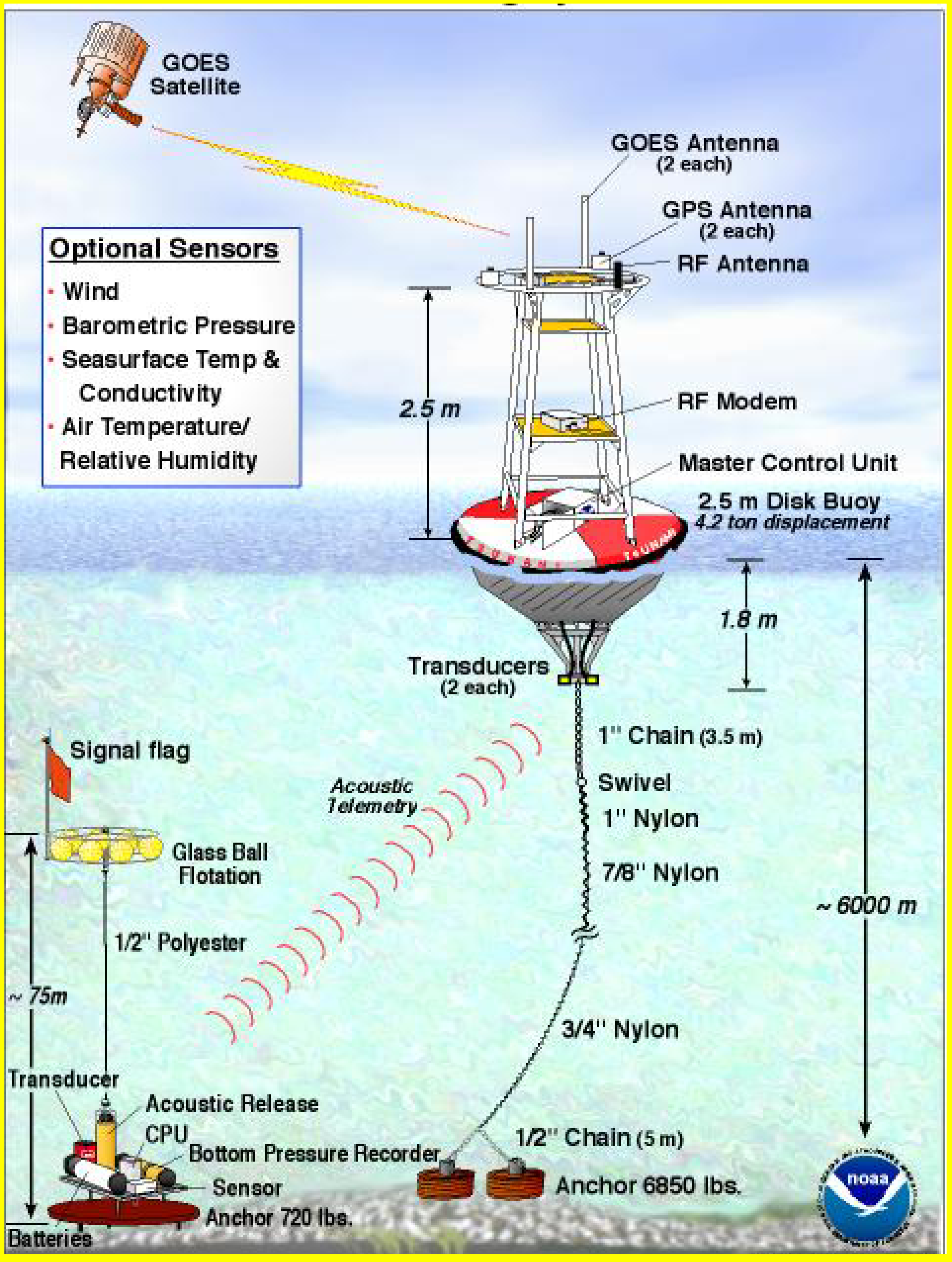
DART Concept

BPR measures small changes in pressure at the seafloor. Data sent acoustically to surface buoy, then via satellite to the Warning Centers.

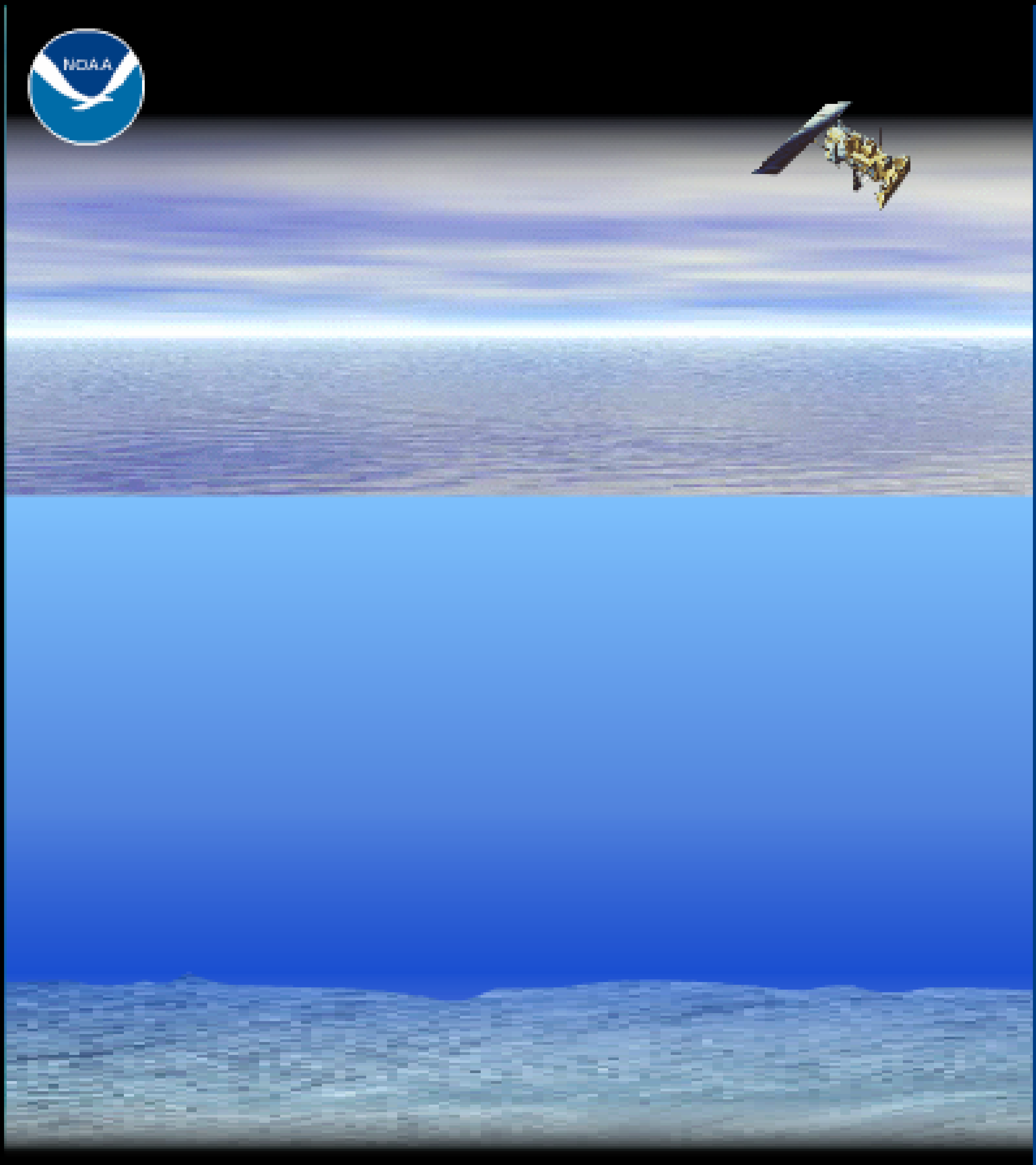
<u>Normal transmissions</u>: Hourly reporting of 15 minute data to confirm system readiness.

<u>Two Event Modes</u>:

- *<u>Automatic</u>*: Triggered by seismic or tsunami wave
- *<u>Request</u>*: Warning Center triggers data stream



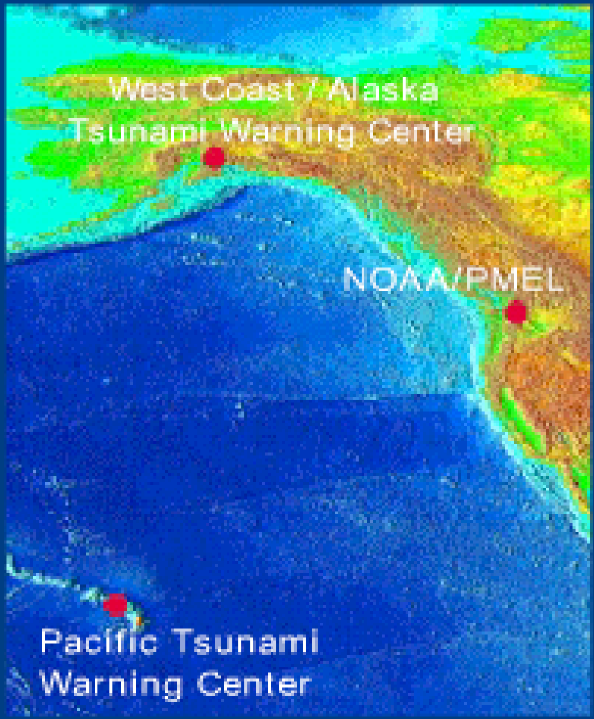
<u>Animation</u>



Deep Ocean Assessment and Reporting of Tsunamis

Tsunami Warning Centers

Trigger Mode | Request Mode



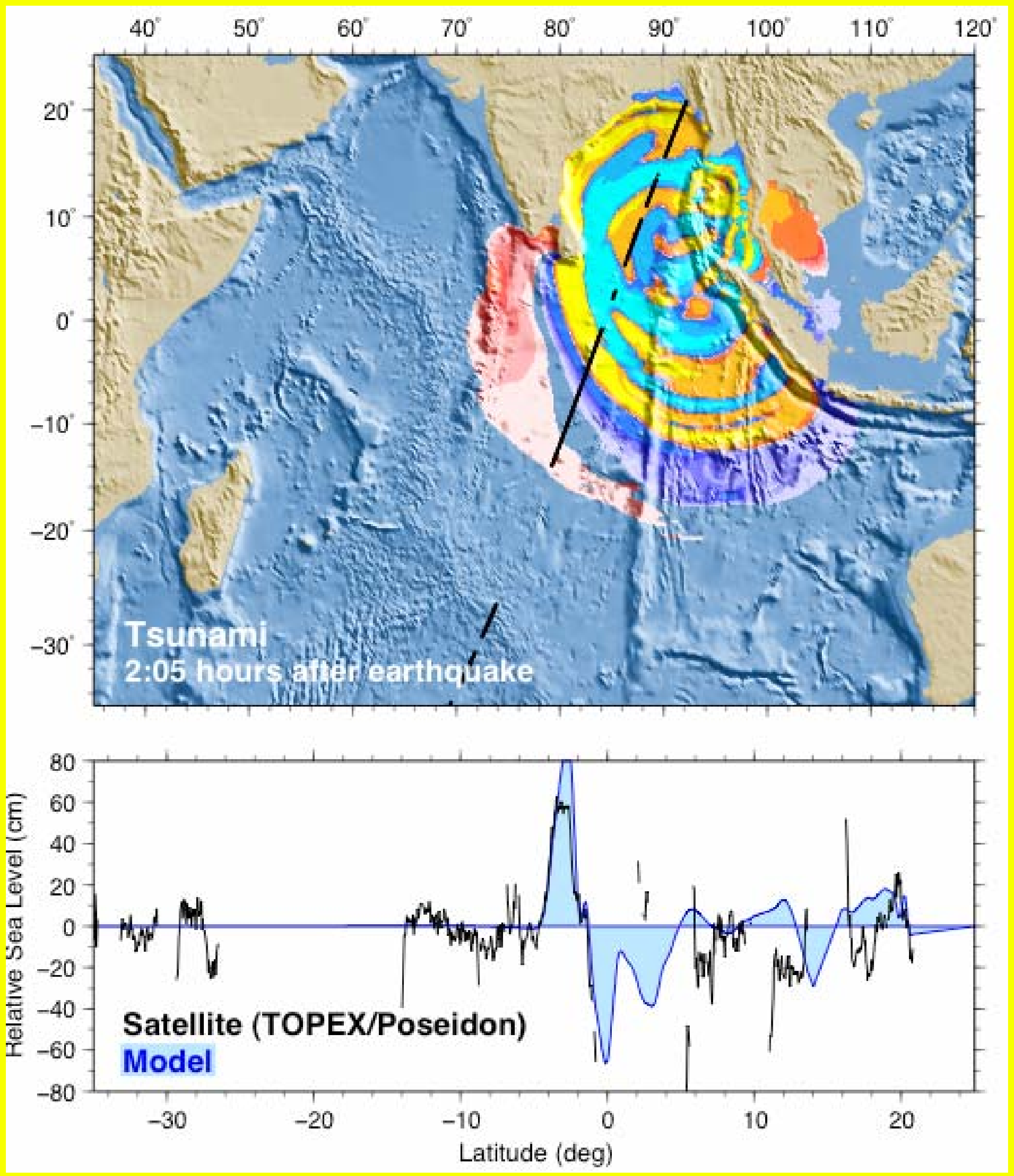
JASON-1 Altimeter Comparison with Tsunami Model

NOAA

Laboratory for Satellite Altimetry:

Remko Scharroo
Walter H. F. Smith

Pac. Mar. Env. Lab.
Vasily Titov

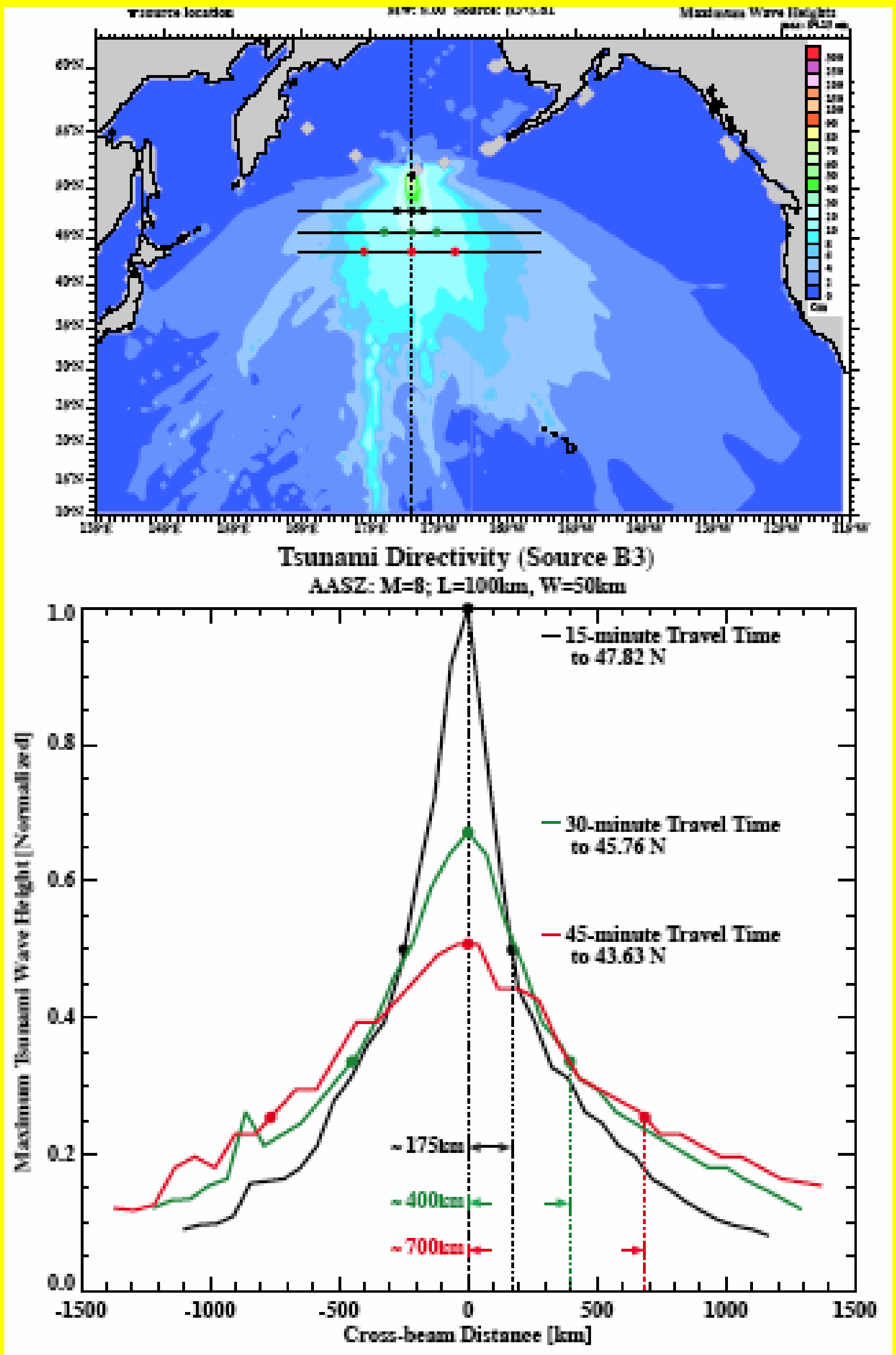


Tsunami Forecasting Measurement Requirements

1. Measurement type - tsunami amplitude over time for input into forecast models
2. Measurement accuracy - 0.5 cm
3. Measurement sample rate – 1 min or less
4. Measurement processing – within 2 min
5. Measurement availability – within 5 minutes to assimilate into forecast models

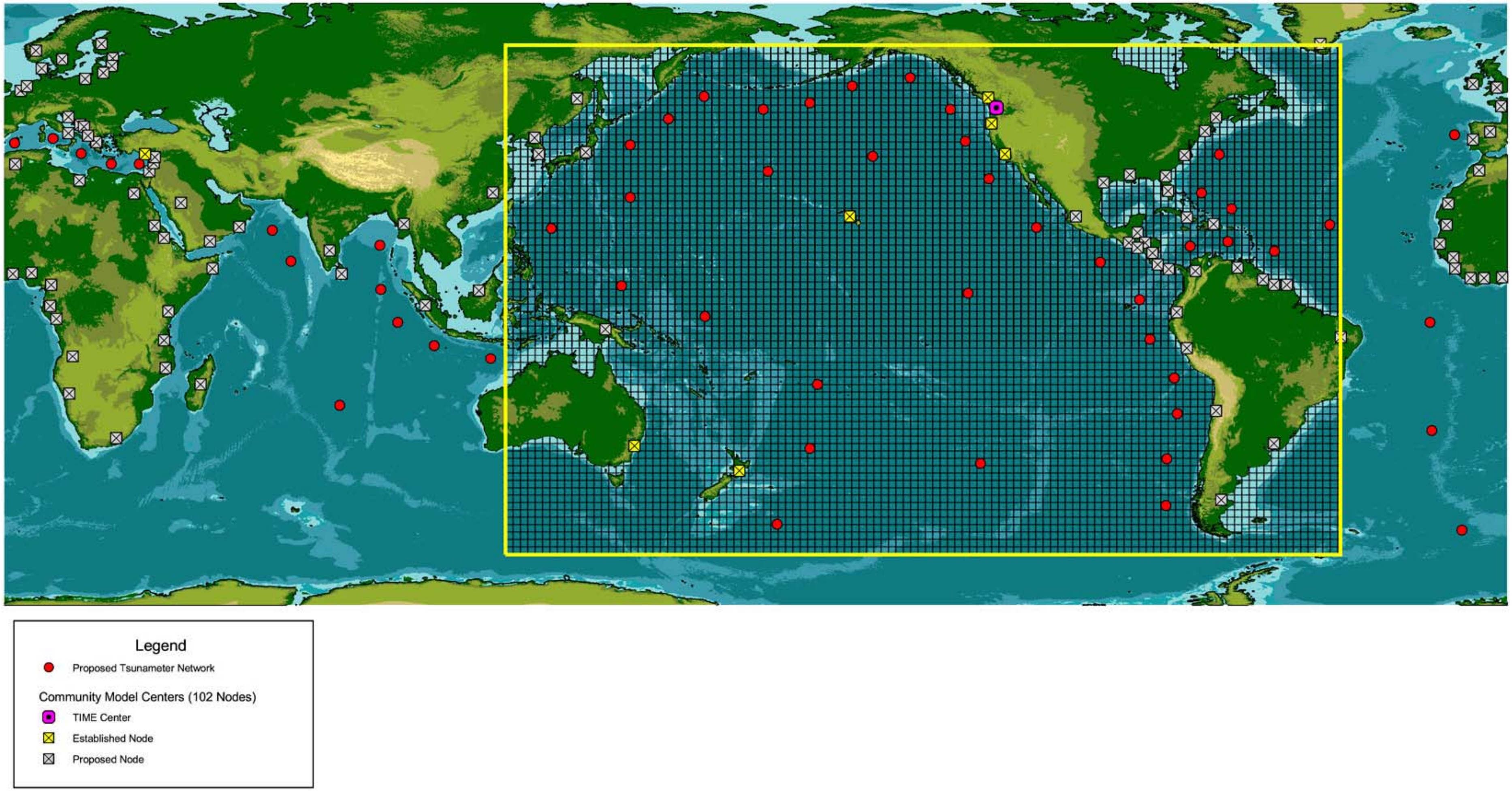
How many tsunameters are needed ?

- At least 3 measurements on main beam
- 9000 km ~ length of Pacific tsunamigenic zones
- Number of tsunameters
  ~ 15 for 45-min TT
  ~ 25 for 30-min TT
  ~ 50 for 15-min TT
- More required for M < 8



Frank I. González, NOAA/PMEL, Seattle, WA, USA

NOAA Tsunami Forecasting System



DART Deployments in AASZ - October 1999

Operational Tsunami Forecasting

- **Essential to Improve Warning Speed and Reliability**
- **Vast Ocean Areas with No Tsunami Measurements**
- **Must Integrate Real-time Measurement and Modeling**
  - ***Measurement: NOAA DART Network***
  - ***Modeling: NOAA Tsunami Forecast Model***

Operational Tsunami Forecasting

- **Must Integrate Real-time Measurement and Modeling**
  - ***- Measurement:*** ***NOAA DART Network***
  - ***- Modeling:*** ***NOAA Tsunami Forecast Model***

- **Real-time Methodologies**
  - ***- Inversion:*** ***Force Model to Match Real-time Data***
  - ***- Interpolation:*** ***Model Values for Areas with No Data***
  - ***- Forecast:*** ***Real-time Inundation Simulations***

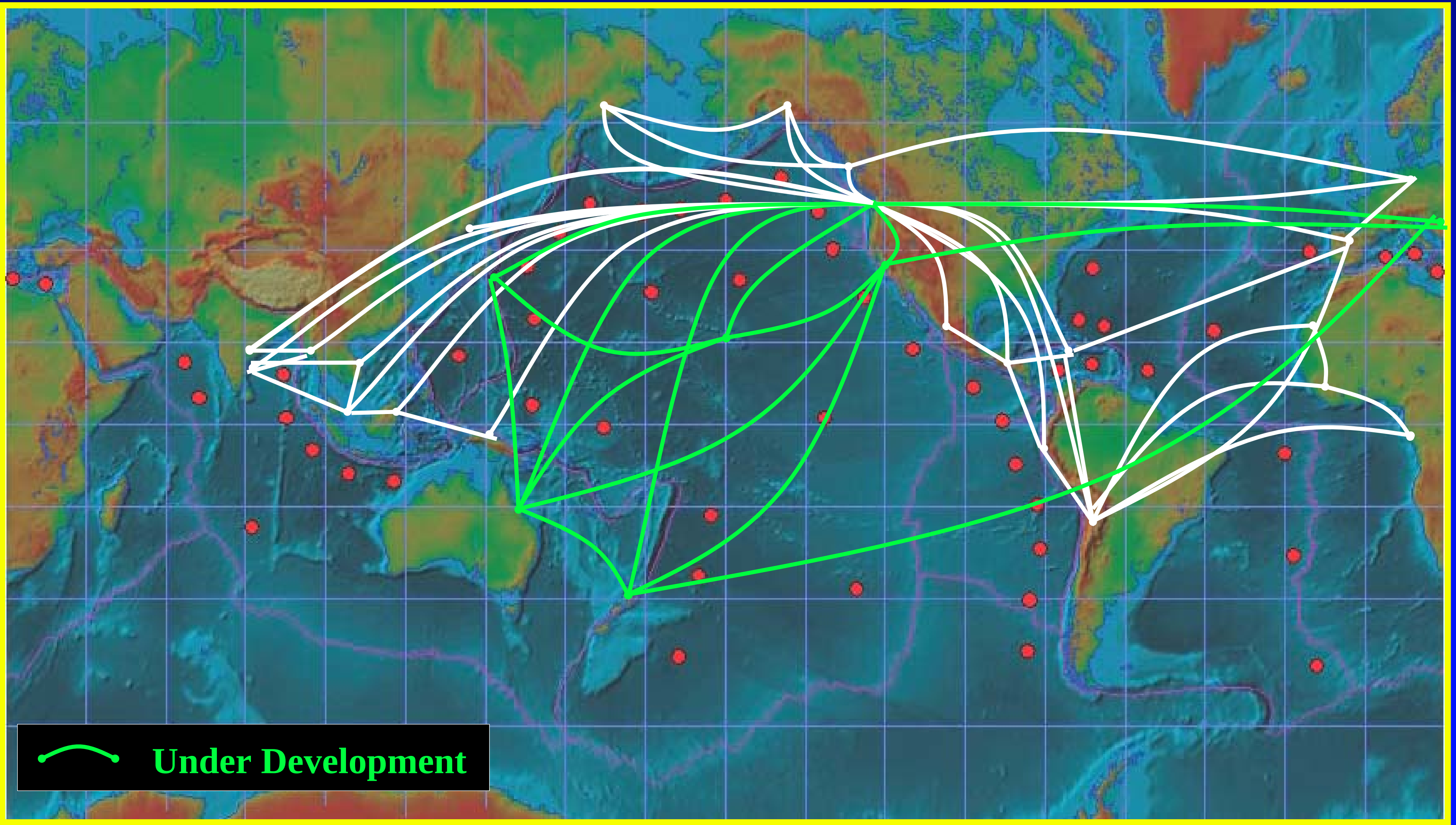
- **International Modeling Network**

  Transfer, Maintain, and Improve Tsunami Forecast Models

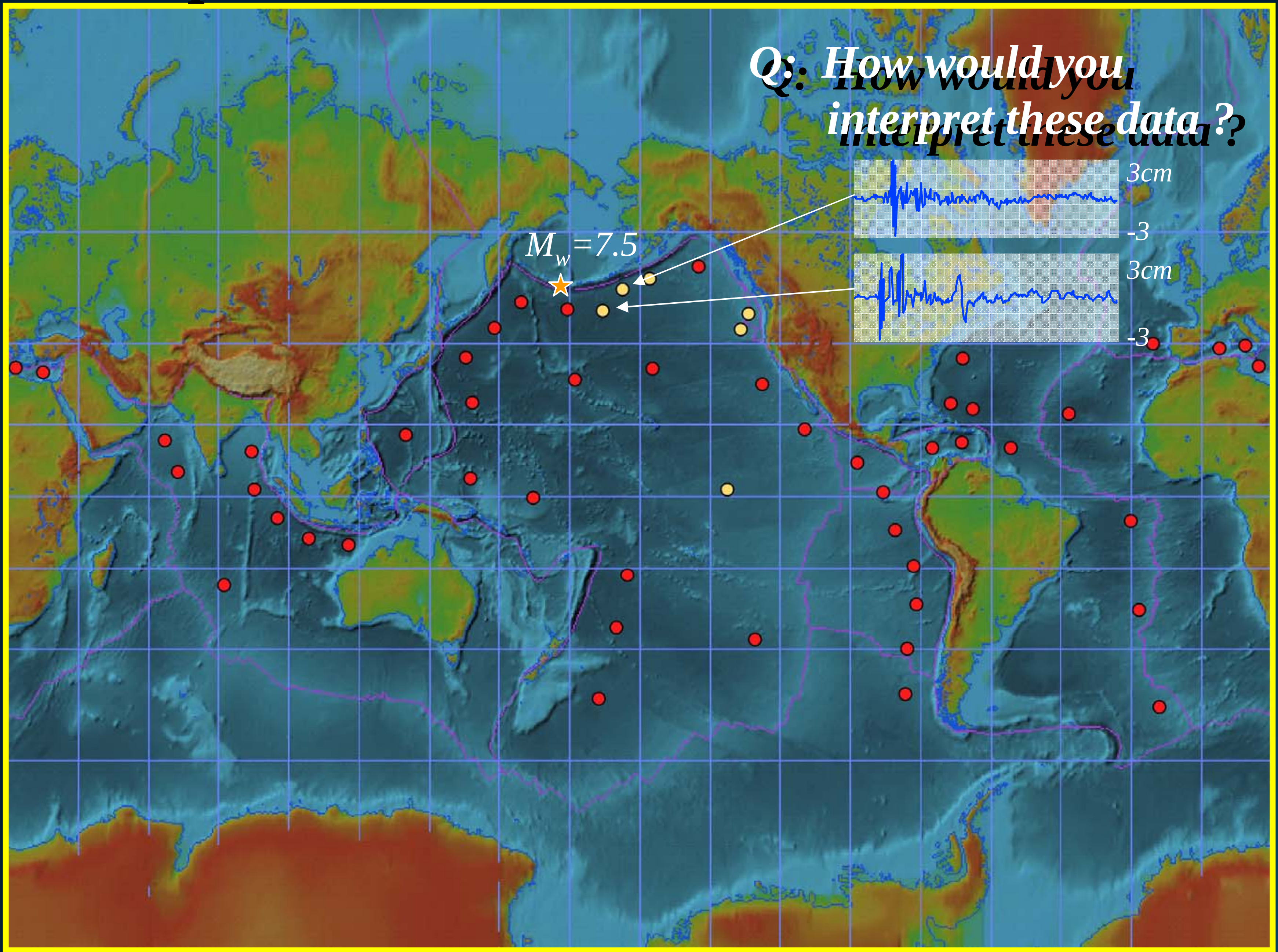
International Modeling Network

Transfer, Maintain, and Improve Tsunami Forecast Models

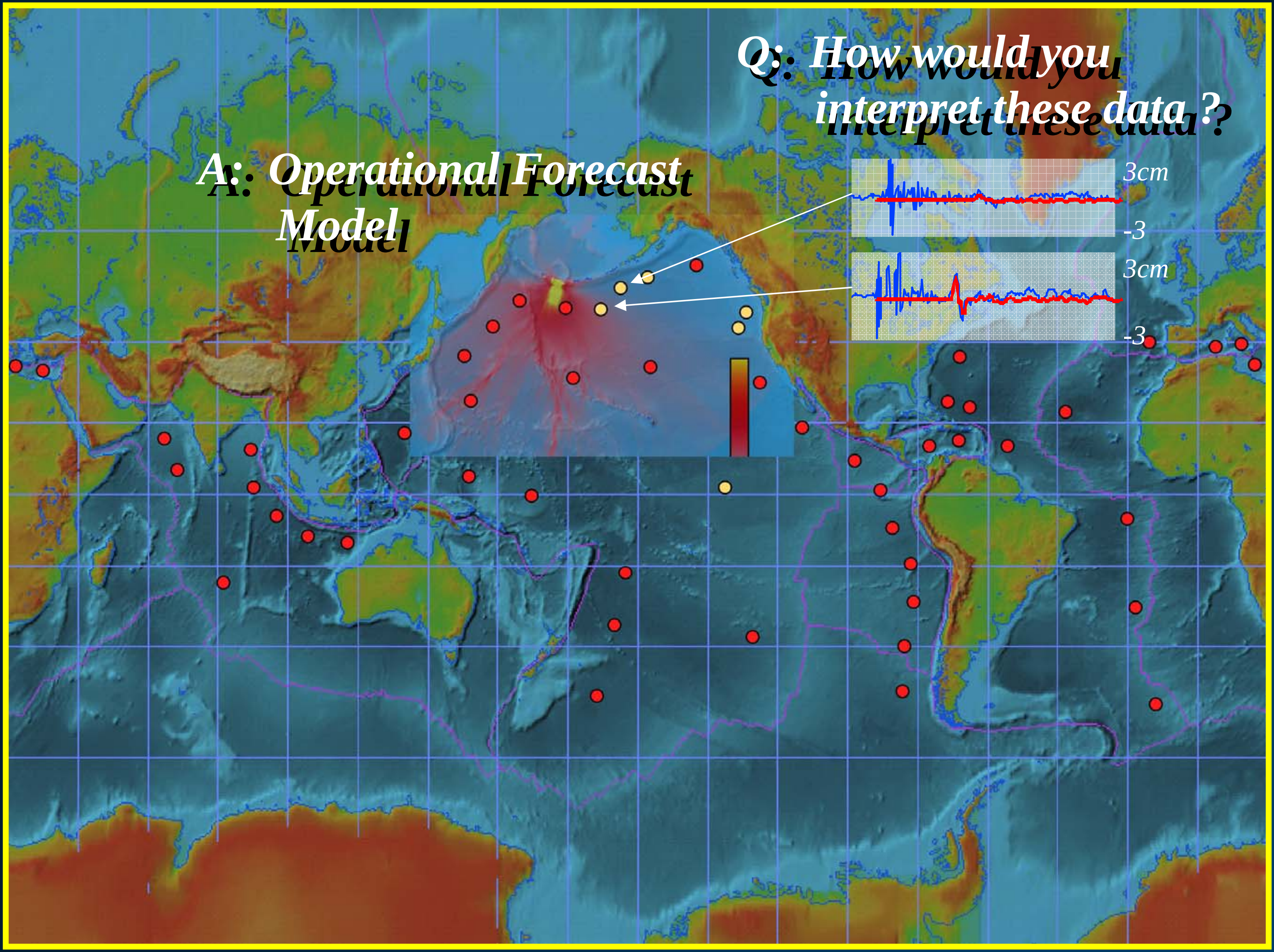
Network Nodes Share: Models, R&D Tools, Databases, …



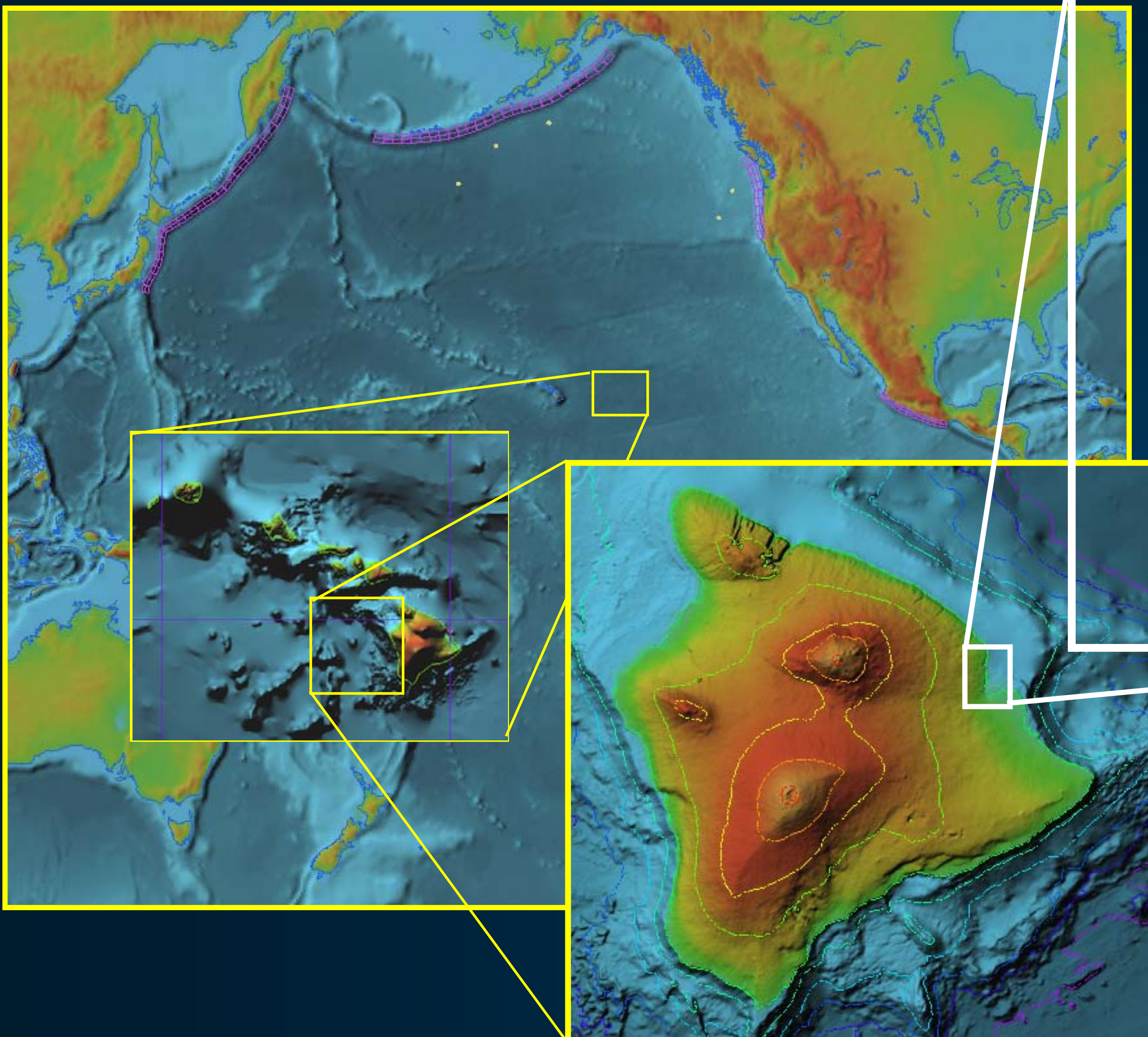
Example of Tsunami Forecast: 17 Nov 2003



Example of Tsunami Forecast: 17 Nov 2003



1. Pre-computed Nested Grid Database of Offshore Values

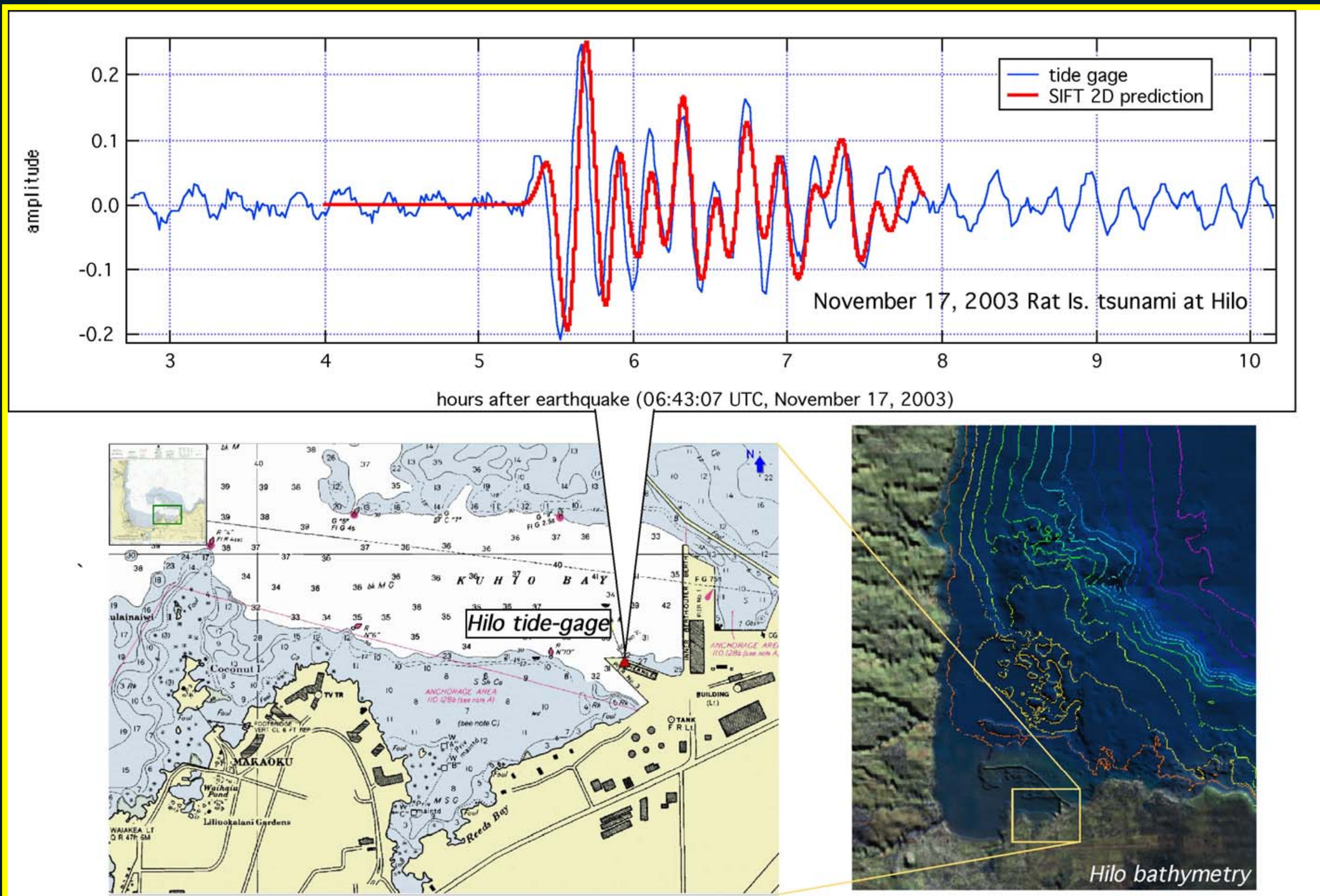


QuickTime™ and a Photo decompressor are needed to see this picture.

• Hilo Tide Gage

2. Provides Initial Conditions for Real-time Inundation Simulation (~10 Minutes)

Result: "Blind" Tsunami Forecast at Hilo



Summary

- Sumatra mega-disaster a global wake-up call
- Tsunamis are inevitable
- U.S. accelerating Tsunami Preparedness efforts
  - Assessment
  - Education, Outreach
  - Tsunami Forecasting and Warning System

Thanks …